Journal of
THE CHEMICAL SOCIETY

Publication Committee

Chairman: C. K. Ingold, D.Sc., F.R.I.C., F.R.S.

C. C. Addison, D.Sc., Ph.D., F.R.I.C.
G. Baddeley, Ph.D., D.Sc., F.R.I.C.
D. H. R. Barton, D.Sc., F.R.I.C., F.R.S.
F. Bergel, D.Phil.Nat., D.Sc., F.R.I.C.
E. Boyland, D.Sc., Ph.D.
J. Chatt, M.A., Sc.D., F.R.I.C.
P. B. D. de la Mare, D.Sc., Ph.D.
H. J. Emeléus, D.Sc., A.R.C.S., F.R.S.
D. H. Everett, M.B.E., M.A., D.Phil., F.R.S.E.
G. Gee, Sc.D., A.R.I.C., F.R.S.
B. A. Hems, D.Sc., F.R.I.C.
E. L. Hirst, M.A., D.Sc., LL.D., F.R.S.
H. R. Ing, M.A., D.Phil., F.R.S.
H. M. N. H. Irving, M.A., D.Phil., F.R.I.C.
D. J. G. Ives, D.Sc., A.R.C.S., F.R.I.C.
E. R. H. Jones, D.Sc., F.R.I.C., F.R.S.
G. W. Kenner, M.Sc., Ph.D.
H. C. Longuet-Higgins, M.A., D.Phil.
B. Lythgoe, M.A., Ph.D., F.R.I.C.
R. A. Morton, D.Sc., Ph.D., F.R.S.
A. Neuberger, Ph.D., M.D., F.R.S.
R. G. W. Norrish, Sc.D., F.R.I.C., F.R.S.
M. W. Perrin, C.B.E., M.A., F.R.I.C.
V. Petrow, Ph.D., D.Sc., F.R.I.C.
H. M. Powell, M.A., B.Sc., F.R.S.
P. L. Robinson, D.Sc., F.R.I.C.
K. Schofield, Ph.D., D.Sc., F.R.I.C.
N. Sheppard, M.A., Ph.D.
M. Stacey, Ph.D., D.Sc., F.R.S.
L. E. Sutton, M.A., D.Phil., F.R.S.
H. W. Thompson, M.A., D.Sc., F.R.S.
E. E. Turner, M.A., D.Sc., F.R.S.
A. R. J. P. Ubbelohde, M.A., D.Sc., F.R.S.

Editor

R. S. Cahn, M.A., D.Phil.Nat., F.R.I.C.

Assistant Editors

A. D. Mitchell, D.Sc., F.R.I.C.
L. C. Cross, Ph.D., A.R.C.S., F.R.I.C.
A. E. Somerfield, Ph.D.

SEPTEMBER, 1956

Subscription rate to non-Fellows £10 0s. 0d. per annum post free.

LONDON: THE CHEMICAL SOCIETY, BURLINGTON HOUSE, W.1

THE CHEMICAL SOCIETY

PATRON
HER MAJESTY THE QUEEN

President
E. L. Hirst, M.A., D.Sc., LL.D., F.R.S.

Vice-Presidents
who have filled the office of President

Sir Ian Heilbron, D.S.O., D.Sc., LL.D., F.R.S.
Sir Cyril Hinshelwood, M.A., Sc.D., F.R.S.
C. K. Ingold, D.Sc., F.R.I.C., F.R.S.
W. H. Mills, M.A., Sc.D., F.R.S.
Sir Eric Rideal, M.B.E., M.A., D.Sc., F.R.S.
W. Wardlaw, C.B.E., D.Sc., F.R.I.C.

Vice-Presidents

E. D. Hughes, D.Sc., F.R.I.C., F.R.S.
E. R. H. Jones, D.Sc., F.R.I.C., F.R.S.
R. P. Linstead, C.B.E., M.A., D.Sc., F.R.S.
H. W. Melville, D.Sc., F.R.I.C., F.R.S.
M. Stacey, Ph.D., D.Sc., F.R.S.
Sir Alexander Todd, M.A., D.Sc., F.R.S.

Honorary Treasurer
M. W. Perrin, C.B.E., M.A., F.R.I.C.

Honorary Secretaries

L. E. Sutton, M.A., D.Phil., F.R.S.
F. Bergel, D.Phil.Nat., D.Sc., F.R.I.C.
J. Chatt, M.A., Sc.D., F.R.I.C.

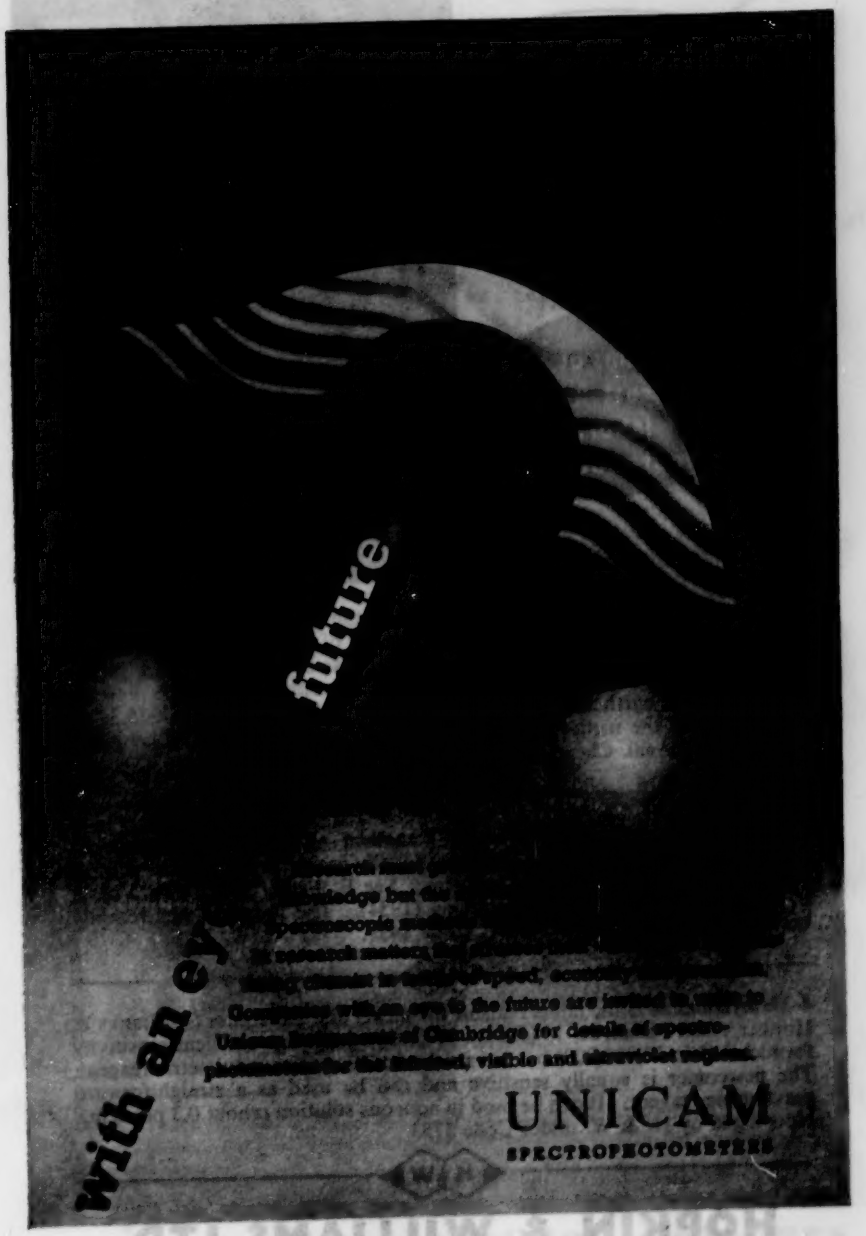
Ordinary Members of Council

D. W. Adamson, M.Sc., D.Phil., A.R.I.C.
C. C. Addison, D.Sc., Ph.D., F.R.I.C.
G. R. Barker, B.Sc., Ph.D.
R. M. Barrer, D.Sc., Sc.D., F.R.S.
V. C. Barry, D.Sc., M.R.I.A., F.I.C.I., F.R.I.C.
F. Bell, D.Sc., F.R.I.C., F.R.S.E.
A. G. Evans, Ph.D., D.Sc., F.R.I.C.
A. Hickling, D.Sc., Ph.D., F.R.I.C.
L. Hunter, Ph.D., D.Sc., F.R.I.C.
H. M. N. H. Irving, M.A., D.Phil., F.R.I.C.
G. W. Kenner, M.Sc., Ph.D.
B. Lythgoe, M.A., Ph.D., F.R.I.C.
A. Maccoll, M.Sc., Ph.D.
F. H. Pollard, B.Sc., Ph.D.
J. M. Robertson, M.A., D.Sc., F.R.S.
H. N. Rydon, D.Sc., D.Phil., F.R.I.C.
H. D. Springall, M.A., D.Phil., F.R.I.C.
L. A. K. Staveley, M.A.
W. Wild, B.Sc., Ph.D., A.R.I.C.
G. T. Young, Ph.D., M.A., A.R.I.C.

General Secretary
J. R. Ruck Keene, M.B.E., T.D., M.A.

Librarian
R. G. Griffin, F.L.A.

Deputy Librarian
J. Bird


future
with an eye
UNICAM
SPECTROPHOTOMETERS

Incidental information
No. 10

items of interest from our laboratory notebooks

Metal indicators have contributed much to the applications of Sequestric Acid (EDTA), and H. & W. have made a series of these indicators available. **1-(2-Pyridylazo)-2-naphthol,** for example, is used as an indicator in the titration of zinc, copper, and cadmium with Sequestric Acid in the presence of the alkaline earth metals. It is listed under H. & W. Code 7275.3. A description of the methods will be found in a paper by K. L. Cheng and R. H. Bray. **Anal. Chem., 27,** 782 (1955).

H W

Tetrabromophenolphthalein ethyl ester (potassium salt) is an indicator that has been put to a novel purpose. Its exceptionally great ' protein error ' affords a method for the detection of proteins. See F. Feigl, **Spot Tests,** Vol. 2, p. 293. Elsevier Publishing Company (1954). The indicator has recently become available under H. & W. Code 8439.

H W

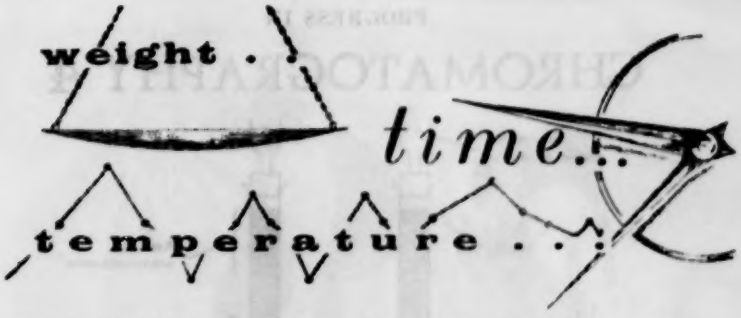
4-Methylnioxime is the latest reagent for nickel and palladium (see Banks & Hooker, **Anal. Chem., 28,** 79 (1956)). Nioxime itself has excellent sensitivity for nickel (1 in 10,000,000) but has its shortcomings as a gravimetric reagent. The newcomer is equally sensitive and can be used as a straightforward gravimetric reagent. It can be used in aqueous solution (about 0.3 per cent). Now listed by H. & W. under Code 5753.

H W

HOPKIN & WILLIAMS LTD.

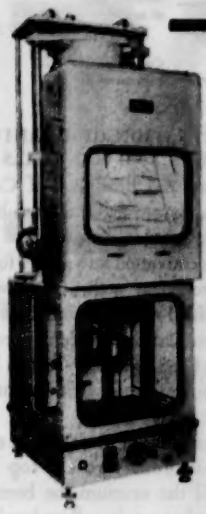
Manufacturers of pure chemicals for Research and Analysis

CHADWELL HEATH · ESSEX · ENGLAND



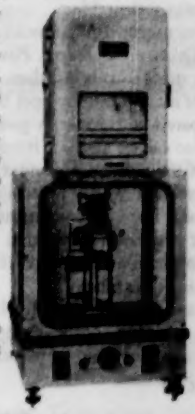
recorded simultaneously and continuously by the

stanton thermo-balance



Once set, the new Stanton thermo-balance will reproduce and record weight changes, time and temperature for periods up to several days. The many applications of this precision balance include the recording of ignitions or similar studies; determination of moisture, volatile and ash; preparation of oxidation curves; oxidation rates on metal powders; investigation of sublimation phenomena; evaporation rates of solvents, etc.

The Stanton thermo-balance is air-damped and suitable for a total load of 100 grammes; it may be supplied with a sensitivity of 1 mg. or 1/10th mg. The standard furnace (as illustrated) is suitable for 1,000° C. but alternative furnaces for both low and high temperatures can be made. Furnace temperature and change of weight are followed simultaneously on a twin pen electronic recorder, (incorporating Fielden "Servograph" patents).



STANTON RECORDING BALANCE

Similar to the thermo-balance, but without a furnace; the twin recorder is replaced with a single range instrument which records weight and time alone on a 5 in. chart.

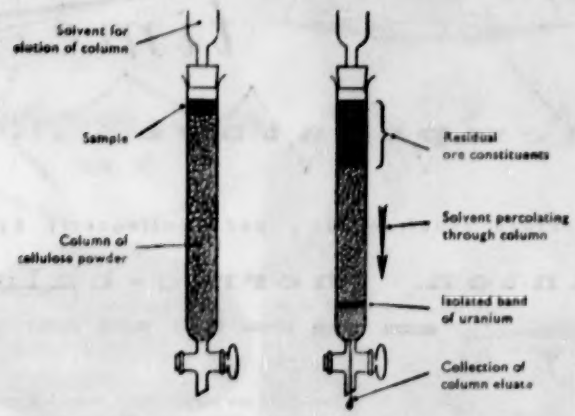
Both balances incorporate an automatic timing device which operates the arrestment mechanism at known time intervals. Full details of these precision instruments are included in the Stanton catalogue—sent free on request.

stanton precision balances

STANTON INSTRUMENTS LTD. Dept. TCS/2., 119 Oxford Street, London, W.1.
Telephone: GERrard 7533.

PROGRESS IN

CHROMATOGRAPHY 4



COLUMN CHROMATOGRAPHY USING CELLULOSE POWDER

One of the most useful features of filter paper chromatography is the minute scale on which separation can be effected. Described below is an extension of the principle for applications in which the separation of larger quantities is desirable.

In this method Whatman "Ashless" or "B - Quality" Cellulose Powder is packed into a tube, usually of glass. Because of the greater mass of cellulose per theoretical plate (compared with paper) a greater amount of mixture can be applied. Introduced into the top of the column, this mixture is followed by a solvent which percolates through the column. The components are carried with it, but at different rates; thus separated, they are collected in successive fractions at the bottom of the tube.

Column Chromatography has made most rapid progress in the inorganic field, but interesting organic applications have also been published.

DETERMINATION OF URANIUM IN ORES AND MINERALS

The simplicity and flexibility of Column Chromatography are demonstrated by this established analytical technique.

The sample is converted into nitrate form by fusion and treatment with acid. Powdered cellulose is added to a few millilitres of the dilute solution and the whole is introduced into the top of the column to form a homogeneous continuation with the original cellulose.

A solvent consisting of nitric acid in ether is applied continuously to the top of the column, until the uranium has been completely isolated as a pale yellow band at the bottom.

Uranium can be quantitatively separated from many complex materials by this method in a state of absolute purity. Similar methods are used in many other types of inorganic analysis.

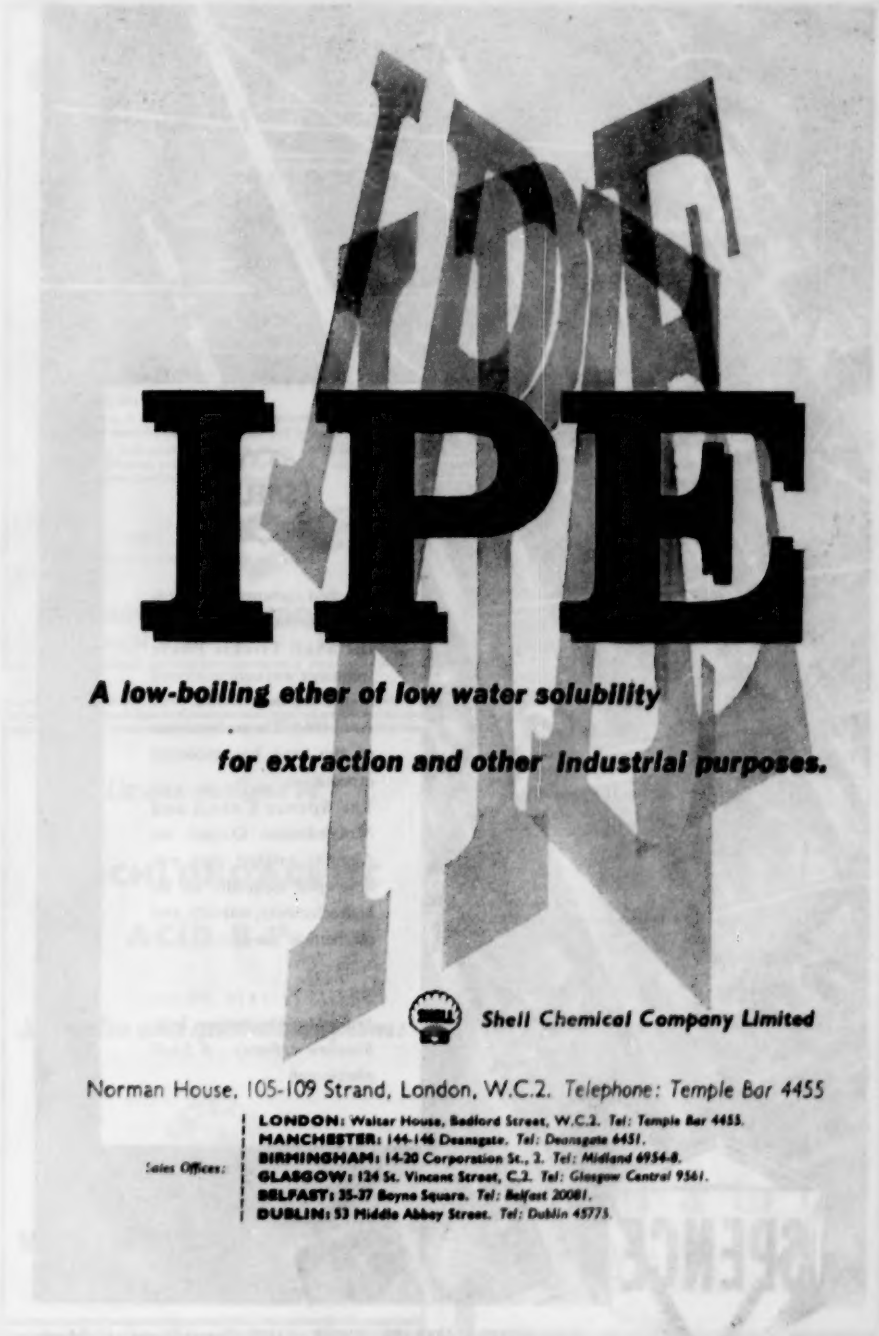
Now that you have read this report it may occur to you that Chromatography can help you in your research or production programme. If so, our long experience in this specialised field is at your full disposal. Discuss the possibilities of Chromatography with

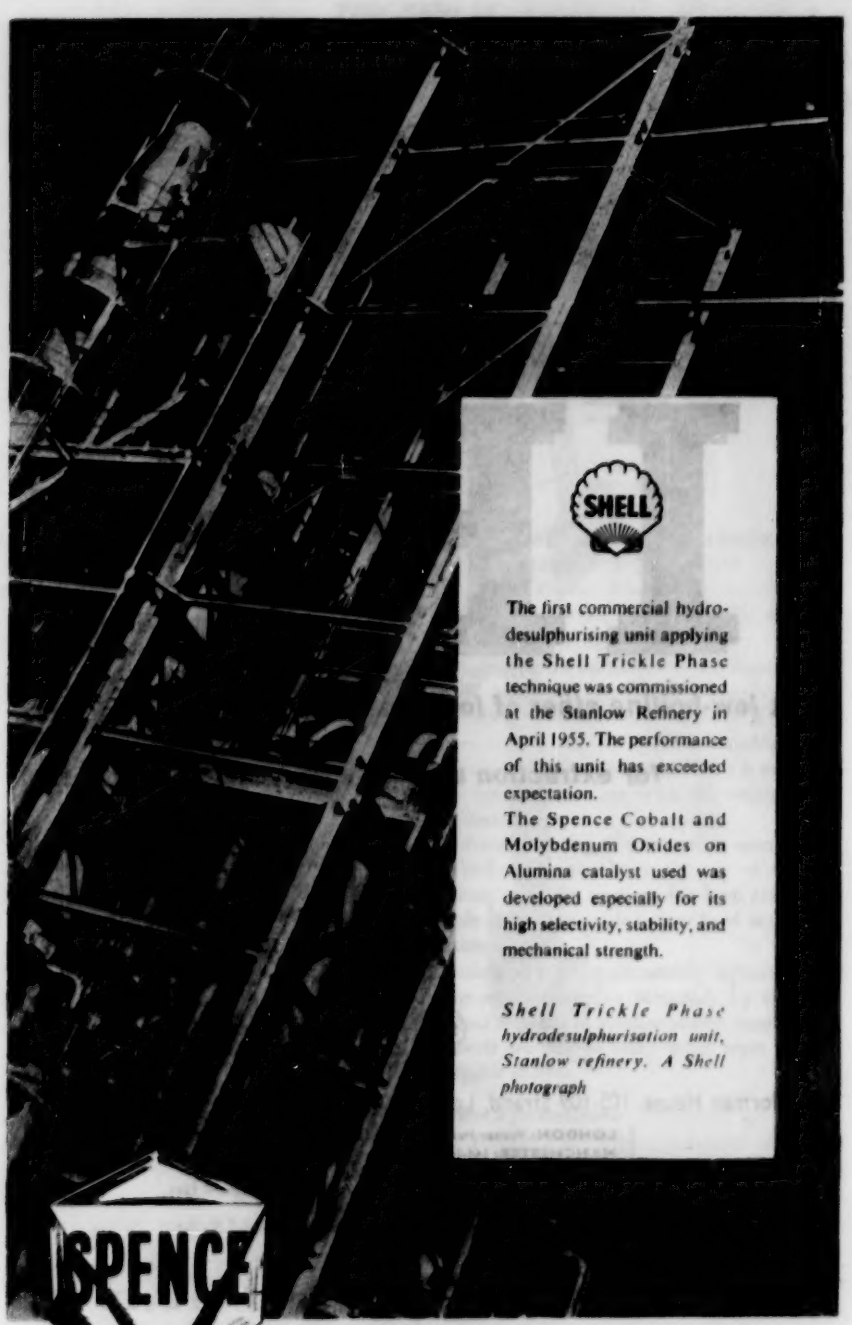
H. REEVE ANGEL & CO. LTD.
9 BRIDEWELL PLACE, LONDON, E.C.4.

Sole distributors of

WHATMAN FILTER PAPERS

(Manufacturers W. & R. Balston Ltd.)


IPE
A low-boiling ether of low water solubility
for extraction and other industrial purposes.
Shell Chemical Company Limited
Norman House, 105-109 Strand, London, W.C.2. Telephone: Temple Bar 4455
Sales Offices:
LONDON: Walter House, Bedford Street, W.C.2. Tel: Temple Bar 4455.
MANCHESTER: 144-146 Deansgate. Tel: Deansgate 6451.
BIRMINGHAM: 14-20 Corporation St., 2. Tel: Midland 6954-8.
GLASGOW: 124 St. Vincent Street, C.2. Tel: Glasgow Central 9561.
BELFAST: 35-37 Boyne Square. Tel: Belfast 20081.
DUBLIN: 53 Middle Abbey Street. Tel: Dublin 45775.


SHELL
The first commercial hydrodesulphurising unit applying the Shell Trickle Phase technique was commissioned at the Stanlow Refinery in April 1955. The performance of this unit has exceeded expectation.
The Spence Cobalt and Molybdenum Oxides on Alumina catalyst used was developed especially for its high selectivity, stability, and mechanical strength.
Shell Trickle Phase hydrodesulphurisation unit, Stanlow refinery. A Shell photograph
SPENCE
PETER SPENCE & SONS LTD · WIDNES · LANCS Also at London and Bristol

Old Charlie's no chemist- BUT-

when it comes to pH determination he can hold his own against any B.Sc.

Johnson Indicator Papers make it so easy!

UNIVERSAL TEST PAPER will give the pH value of any solution to within 0·5 pH in the range of 1 to 10.

For still greater accuracy the set of four COMPARATOR TEST PAPERS show values from 3·6 to 10 pH in steps of 0·3 pH.

There are, in addition, over 40 different kinds of Test Papers for specific uses in Science and Industry.

All these indicator papers are made up in standard books of 20 leaves and packed in boxes of 6, heat-sealed in cellophane against climatic conditions.

A descriptive leaflet will be sent free on request.

JOHNSONS OF HENDON LTD.
LONDON, N.W.4 EST. 1743

We are makers of:

TRICHLOROACETIC ACID B.P.

Samples and quotations from:

KAYLENE BRAND

KAYLENE (CHEMICALS) LTD.
WATERLOO ROAD, LONDON, N.W.2
TEL: GLADSTONE 1071/2/3

Latest additions to 1956 catalogue

Acetovanillone	12/- H
5-Amino *iso*phthalic acid	75/- H
DL-Benzoyl-α-alanine	42/- H
DL-ε-Benzoyllysine	50/- H
DL-Benzoyl phenylalanine	27/- D
DL-Benzoylvaline	90/- H
Bromoacetal (bromoacetaldehyde diethyl acetal)	44/- H
1-Bromo-2-naphthol	21/- D
2-Chlorocyclohexanone	60/- H
6-Chloropurine	43/- d
Convallamarin	8/- G
L-Cysteine hydantoin	63/- D
L-Cystine hydantoin	52/- D
4, 5-Diamino-pyrimidine	50/- d
L-Dibenzoylcystine	84/- D
2, 5-Dibromothiophene	48/- H
p-Di(chloroethyl)aminophenyl-butyric acid	39/- G
α, β-Dichloro-propionic acid	82/- H
Dicyclopropyl ketone	100/- H
L-Diformylcystine	91/- D
2, 4-Dimethoxy-benzaldehyde	120/- H
2, 4-Dimethyl thiazole	35/- D
L-Diphenacetylcystine	59/- D
Diphenyl phosphoryl chloride	42/- H
Ethyl *iso*butyl ketone	170/- H
2-Ethyl hexoic acid	32/- K
Flavin adenine dinucleotide (FAD)(85% ± 5%)(25 mgm. amps.)	138/- A
Hexamethylene dibromide	40/- H
Hexamethylene dinitrile	93/- H
Hydrobenzoin	35/- D
p-Hydroxy-phenylacetic acid	39/- D
L-Leucine (free from methionine)	62/- H
Methyl formanilide	150/- K
O-Methyl-DL-serine	6/- G
N-Morpholylacetal	185/- H
m-Nitrobenzonitrile	36/- D
4-Nitropyridine-N-oxide	19/- D
5-Nitro-quinoline	38/- D
Potassium phenolphthalein di-sulphate	50/- D
Pyridine-2-aldoxime methiodide (2-PAM)	197/- G
Pyridine-2-aldoxime	65/- H
Pyridine-3-aldoxime	80/- H
Pyridine-4-aldoxime	75/- H
Pyridine-2, 6-dialdoxime	110/- H
Pyridoxal-5'-phosphate (cryst.)	98/- G
Quinoline-N-oxide dihydrate	26/- D
m-Sulphobenzoic acid	20/- D
Triphenylphosphine	44/- D
Vitamin A alcohol (synthetic, cryst.)	33/- G

L. LIGHT & Co Ltd
POYLE TRADING ESTATE
COLNBROOK BUCKS ENGLAND

MANSFIELD OIL-GAS PLANT
FOR LABORATORIES' GAS SUPPLY

Laboratories without a supply of gas should write for particulars of this Plant which produces gas in a simple manner from any cheap oil such as Solar Oil. . . . The gas produced has a calorific value of 1,350 B.T.U.'s per cubic foot, and is suitable for use with any appliance designed for use with coal gas and gives perfect oxidising and reducing flames.

MANSFIELD & SONS LTD
62 HAMILTON SQUARE, BIRKENHEAD

Today, more than ever, industry looks to ERMETO for efficient high-pressure pipe lines

Whatever the field of application you will find ERMETO valves and couplings have played a notable part in raising the standard of efficiency. *Technical literature gladly sent on request.*

ERMETO

VALVES & COUPLINGS

BRITISH ERMETO CORPORATION LIMITED
Maidenhead, Berks. Tel: 2271/4

H. K. LEWIS
BOOKS ON THE CHEMICAL AND ALLIED SCIENCES

Scientific and Technical Books :: Large Stock of Recent Editions.
Foreign Books not in Stock obtained to order :: Catalogues on request.

LENDING LIBRARY—Scientific and Technical

ANNUAL SUBSCRIPTION FROM £1 17s. 6d. PROSPECTUS FREE ON APPLICATION

THE LIBRARY CATALOGUE containing classified Index of Authors and Subjects revised to December 1949. Pp. xii + 1152. To subscribers 17s. 6d. net. To non-subscribers 35s. net., postage 1s. 8d. Supplement 1950 to 1952. To subscribers 1s. 6d. net; to non-subscribers 3s. net; postage 9d.

BI-MONTHLY LIST OF NEW BOOKS AND NEW EDITIONS ADDED TO THE LIBRARY POST FREE TO SUBSCRIBERS REGULARLY

H. K. LEWIS & Co. Ltd., 136 Gower Street, London, W.C.1
Telephone: EUSton 4282 (7 lines)

$HFSO_3$

FLUOSULPHONIC ACID

This is a colourless or pale straw-coloured, mobile, liquid which fumes in moist air.

It is a remarkably stable compound and can be redistilled in glass apparatus.

PHYSICAL PROPERTIES

Boiling point at 760mm.	163°C.
Freezing point	−87.3°C.
Sp. Gr. at 15.6°C.	1.743

Used as a catalyst in condensation and alkylation reactions; for the preparation of alkyl and aryl fluosulphonates, acyl fluorides and aromatic sulphonyl fluorides. As a tool in preparative chemistry, it is similar to chlorosulphonic acid but is generally more stable.

With boric acid it gives boron trifluoride in an easily controlled reaction which forms a convenient method of generating small amounts of that gas.

It has been used in the electropolishing of certain metals.

Advice on materials of construction and on handling, may be obtained from

IMPERIAL SMELTING

A DIVISION OF THE CONSOLIDATED ZINC CORPORATION LIMITED

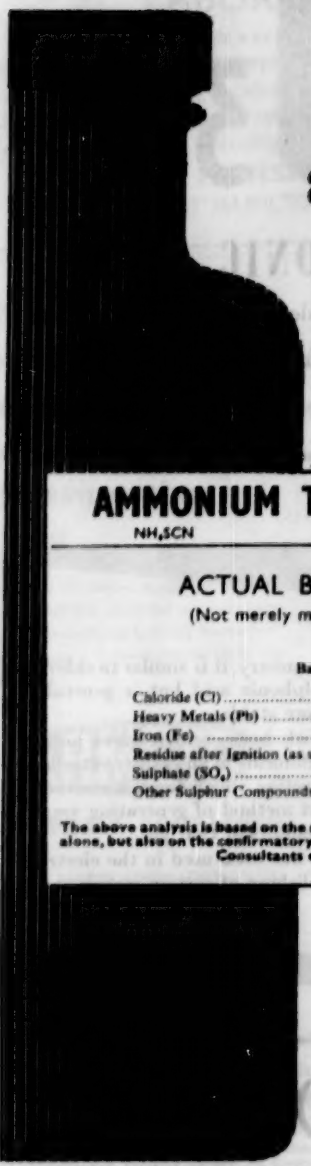
IMPERIAL SMELTING CORPORATION (SALES) LTD., 37 DOVER ST., LONDON, W.1

PIONEERS IN FLUORINE DEVELOPMENT

the outstanding purities of

Judactan

analytical reagents



We invite you to compare the actual batch analysis shown here, with the purities guaranteed by the specifications to which you normally work — we are sure the comparison will be helpful to you.

AMMONIUM THIOCYANATE A.R.

NH_4SCN Mol. Wt. 76·12

ACTUAL BATCH ANALYSIS

(Not merely maximum impurity values)

Batch No. 60207

Chloride (Cl)	0·002%
Heavy Metals (Pb)	0·0001%
Iron (Fe)	0·0001%
Residue after Ignition (as sulphates)	0·052%
Sulphate (SO_4)	0·0003%
Other Sulphur Compounds	no reaction

The above analysis is based on the results, not of our own Control Laboratories alone, but also on the confirmatory Analytical Certificate issued by independent Consultants of international repute

This is the analysis of a Judactan reagent. And, as with every other reagent in the series it is the *actual batch analysis* — it is one of several of which we are especially proud.

The General Chemical & Pharmaceutical Co. Ltd., Chemical Manufacturers, Judex Works, Sudbury, Middlesex.

CONTENTS.

PAPERS COMMUNICATED TO THE CHEMICAL SOCIETY.

General, Physical, and Inorganic.

		PAGE
634.	The Hydrolysis of Di*iso*propyl Methylphosphonodithiolate. By R. F. Hudson and L. Keay	3269
642.	Statistical Thermodynamic Interpretation of the Sorption of Water and Methanol by Carbon. By R. M. Barrer and W. I. Stuart	3307
645.	The Formation of Phenyl Radicals from Tetraphenyl-lead. By J. E. Spice and W. Twist	3319
646.	The Decomposition of Mercury Fulminate. By B. E. Bartlett, F. C. Tompkins, and D. A. Young	3323
647.	The Decomposition of Lead Styphnate Monohydrate. By F. C. Tompkins and D. A. Young	3331
651.	Co-ordination Complexes of Methyl Derivatives of Indium and Thallium. By G. E. Coates and R. A. Whitcombe	3351
652.	The Heat of Hydrolysis of Ethyl Orthosilicate and of Chlorotriethoxysilane. By T. Flitcroft and H. A. Skinner	3355
653.	The Preparation and Properties of Some Plutonium Compounds. Part V. Colloidal Quadrivalent Plutonium. By D. W. Ockenden and G. A. Welch	3358
654.	The Absorption of Uncharged Molecules by Ion-exchange Resins. By D. Reichenberg and W. F. Wall	3364
655.	Structure and Reactivity of the Oxy-anions of Transition Metals. Part I. The Manganese Oxy-anions. By A. Carrington and M. C. R. Symons	3373
657.	The Polonium Halides. Part III. Polonium Tetraiodide. By K. W. Bagnall, R. W. M. D'Eye, and J. H. Freeman	3385
660.	A Conductivity Method for the Accurate Determination of Carbon in Low-carbon Steels. By D. F. Dailly and T. A. Elliott	3398
661.	The Thermal Decomposition of Oxamide. By F. M. Tayler and L. L. Bircumshaw	3405
668.	The Fluorination of Tellurium. Ditellurium Decafluoride and Tellurium Oxyfluorides. By R. Campbell and P. L. Robinson	3454
670.	Dielectric Properties of Some Aluminium Soaps and of their Solutions in Toluene. By S. M. Nelson, A. Gilmour, and R. C. Pink	3463
671.	Structural Chemistry of the Alkoxides. Part VII. Secondary Alkoxides of Quadrivalent Cerium and Thorium. By D. C. Bradley, A. K. Chatterjee, and W. Wardlaw	3469
683.	Some Aspects of the System Uranium Trioxide–Water. By J. K. Dawson, E. Wait, K. Alcock, and D. R. Chilton	3531
692.	The Crystal and Molecular Structure of Pteridine. By T. A. Hamor and J. Monteath Robertson	3586
693.	Calculated Bond Lengths in Some Cyclic Compounds. Part IV. Pteridine and Melamine, and a Correlation Curve for C–N Bonds. By T. H. Goodwin and A. L. Porte	3595
696.	The Preparation of Active Solids by Thermal Decomposition. Part IX. The Calcination of Hydrous Ferric Oxide and of Lepidocrocite. By J. F. Goodman and S. J. Gregg	3612

PAGE

699. Radical Exchange in Organometallic Compounds. Part I. The Replacement of Methyl by Trifluoromethyl.
By R. N. HASZELDINE and B. O. WEST 3631

703. Possible *f*-Orbital Hybridization in Uranyl and Related Complexes.
By C. A. COULSON and G. R. LESTER 3650

NOTE :

712. The Viscosities of Iodine Pentafluoride and Ditellurium Decafluoride.
By G. HETHERINGTON and P. L. ROBINSON 3681

Physical Organic

641. Kinetics and Mechanism of Hydrochlorination of the Surface of Rubber Latex Particles.
By MANFRED GORDON and THOMAS CARBARNS. 3298

649. The Kinetics and Mechanisms of Addition to Olefinic Substances. Part III. The Carbonium Ionic Intermediate involved in Addition of Hypochlorous Acid to *iso*-Butene.
By P. B. D. DE LA MARE and ADIB SALAMA 3337

656. Molecular-weight Studies of Dextran.
By G. C. BOOTH and V. GOLD 3380

662. The Fate of Methyl Radicals in the Mechanism of Thermal Decomposition of Metal Alkyls.
By L. H. LONG 3410

678. The Mechanisms of Inhibition and Retardation in Radical Polymerizations. Part III. The Use of a Stable Free Radical as an Inhibitor.
By J. C. BEVINGTON and N. A. GHANEM 3506

680. The Mechanism of the Pinacol–Pinacone Rearrangement. Part I. Catalysis by Strong Monobasic Acids.
By J. F. DUNCAN and K. R. LYNN 3512

681. The Mechanism of the Pinacol–Pinacone Rearrangement. Part II. Catalysis by Sulphuric Acid.
By J. F. DUNCAN and K. R. LYNN. 3519

686. Molecular Polarisability. The C–C, C–O, C=O, C–Cl, C–Br, and C–I Link Polarisabilities, and the Conformations of *cyclo*Pentane, of *cyclo*Hexyl Chloride, Bromide, and Iodide, and of *cyclo*Pentanone, *cyclo*Hexanone, *cyclo*Hexane-1 : 4-dione, Camphor, Paraldehyde, and Tetrahydrofuran.
By (MRS.) C. G. LE FÈVRE and R. J. W. LE FÈVRE 3549

697. Physical Properties and Chemical Constitution. Part XXV. (*a*) Determination of the Orientation Polarization of Alkylpyridines in Benzene Solutions by Two Independent Methods. (*b*) Dipole Moments of Alkylpyridines.
By C. W. N. CUMPER, A. I. VOGEL, and S. WALKER 3621

698. The Kinetics of Alkyl–Oxygen Fission in Ester Hydrolysis. Part V. Diphenylmethyl Esters in Aqueous Acetone.
By G. J. HARVEY and V. R. STIMSON 3629

NOTES :

717. The Effect of Solvent on the Rates of Solvolysis of 1 : 2-Dichloro-2-methylpropane and of 3-Chloro-2-methylpropene, and the Rearrangement of the Latter Chloride in Formic Acid.
By P. B. D. DE LA MARE, K. LEFFEK, and ADIB SALAMA 3686

708. The Mechanism of the Pinacol–Pinacone Rearrangement. Part III. Evidence on General Acid Catalysis.
By J. F. DUNCAN and K. R. LYNN. 3674

Organic

632. Studies on the Diels–Alder Reaction. Part IV. Reduction Products of *cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Octahydro-8-methoxy-1 : 4-dioxochrysene and their Interrelation.
By P. A. ROBINS and JAMES WALKER 3249

633. A New and Specific Aromatisation Reaction. Part I. Direct Conversion of *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Decahydro-8-methoxy-1 : 4-dioxochrysene into 1-Alkoxy-5 : 6 : 11 : 12-tetrahydro-8-methoxychrysenes.
By P. A. ROBINS and JAMES WALKER 3260

PAGE

635. Triterpenoids. Part LIII. The Constitution and Stereochemistry of Butyrospermol.
By WILLIAM LAWRIE, WILLIAM HAMILTON, F. S. SPRING, and H. S. WATSON . 3272

636. Quassin and *neo*Quassin. Part IV.
By R. J. S. BEER, K. R. HANSON, and ALEXANDER ROBERTSON . . . 3280

637. The Interaction of Boron Trichloride with Unsaturated Alcohols and Ethers.
By W. GERRARD, M. F. LAPPERT, and H. B. SILVER 3285

638. Preparation of 1-Oxygenated Steroids. The Reaction of Cholest-1-en-3β-ol with Thionyl Chloride.
By H. B. HENBEST and R. A. L. WILSON 3289

639. A Search for New Trypanocides. Part II. 4-Amino-6-dialkylaminoquinaldines.
By H. BADER 3293

640. Some Reactions of Hæmatoxylin.
By D. J. DUFF 3296

643. Pteridine Derivatives. Part III. Bisdihydropurinyls.
By W. E. FIDLER and H. C. S. WOOD 3311

644. A New Synthesis of 4-Hydroxycoumarins.
By J. F. GARDEN, N. F. HAYES, and R. H. THOMSON 3315

648. Alkenylation with Lithium Alkenyls. Part XIII. 1-Methylvinyl-lithium (*iso*-Propenyl-lithium).
By (the late) E. A. BRAUDE and E. A. EVANS 3333

650. The Oxidation of Derivatives of *o*-Phenylenediamine. Part IV. A New Series of Glyoxalinophenazines derived from Anilino*apo*safranines and their Behaviour on Hydrogenation.
By VINCENT C. BARRY, J. G. BELTON, J. F. O'SULLIVAN, and DERMOT TWOMEY 3347

658. The Lupin Alkaloids. Part XVI. The Synthesis of Externally Compensated Lupanine.
By G. R. CLEMO, R. RAPER, and J. C. SEATON 3390

659. The Resolution of Secondary and Tertiary Alcohols containing the Pyridyl Group.
By ALWYN G. DAVIES, J. KENYON, and KUMAR THAKER 3394

663. Perfluoroalkyl Derivatives of Nitrogen. Part III. Heptafluoronitrosopropane, Perfluoro-2-*n*-propyl-1 : 2-oxazetidine, Perfluoro(methylene-*n*-propylamine), and Related Compounds.
By D. A. BARR and R. N. HASZELDINE 3416

664. Perfluoroalkyl Derivatives of Nitrogen. Part IV. The Synthesis, Properties, and Infrared Spectra of Perfluoroalkyl *iso*Cyanates and Carbamates.
By D. A. BARR and R. N. HASZELDINE 3428

665. Polynuclear Heterocyclic Systems. Part X. The Elbs Reaction with Heterocyclic Ketones.
By G. M. BADGER and B. J. CHRISTIE 3435

666. Polynuclear Hetercyclic Systems. Part XI. Absorption Spectra of Compounds containing Five-membered Rings.
By G. M. BADGER and B. J. CHRISTIE 3438

667. Pteridine Studies. Part IX. The Structure of the Monohydroxypteridines and their *N*-Methyl Derivatives.
By D. J. BROWN and S. F. MASON 3443

669. Nucleotides. Part XXXVIII. An Improved Synthesis of Uridine-diphosphate-glucose (UDPG).
By A. M. MICHELSON and SIR ALEXANDER TODD 3459

672. The Reactivity of 2-Bromopent-2-enoic Acid.
By B. J. P. ALLES and M. U. S. SULTANBAWA 3472

673. Anomalies in the Reduction of 2 : 2′-Diacetyldiphenyl.
By D. MURIEL HALL, JOAN E. LADBURY, MARY S. LESSLIE, and E. E. TURNER . 3475

674. The Structure of the Extracellular Polysaccharide of *Aerobacter aerogenes* A3 (S1) (Klebsiella Type 54).
By G. O. ASPINALL, R. S. P. JAMIESON, and J. F. WILKINSON 3483

675. The Synthesis of Indeno[2,1-*a*]perinaphthene.
By I. M. AITKEN and D. H. REID 3487

676. 2-Acyl Derivatives of Cyclic 1 : 3-Diones. Part III. Ultraviolet and Infrared Absorption Spectra of 2-Acyl*cyclo*hexane-1 : 3-diones.
By W. R. CHAN and C. H. HASSALL 3495

PAGE

677. The 3-Methylcholestanols and their Derivatives.
By D. H. R. Barton, A. da S. Campos-Neves, and R. C. Cookson . . . 3500

679. Sulphanilamide Derivatives: Compounds derived from 2- and 4-Aminoquinazoline and 1-Aminophthalazine.
By H. J. Rodda 3509

682. Studies on Phosphorylation. Part XIV. The Solvolysis by Phenols of Benzyl Phosphates.
By G. W. Kenner and J. Mather. 3524

684. Ethyl *p*-Nitrobenzoylethoxaloacetate.
By J. Forrest, S. B. Hansen, and V. Petrow 3541

685. The Chemistry of Fungi. Part XXVI. Dechloronornidulin.
By F. M. Dean, A. D. T. Erni, and Alexander Robertson 3545

687. Studies in Pyrolysis. Part VII. Model Systems for the Pyrolysis of Poly(ethylene Terephthalate): 2 : 2′-Dibenzoyloxydiethyl Ether, 2-Benzoyloxyethyl Vinyl Ether, and Certain Related Vinyl Ethers.
By H. V. R. Iengar and P. D. Ritchie 3563

688. Electrophilic Substitution. Part III. The Nitration of Phenanthrene.
By M. J. S. Dewar and E. W. T. Warford 3570

689. Electrophilic Substitution. Part IV. The Nitration of Diphenyl, Chrysene, Benzo[*a*]pyrene, and Anthanthrene.
By M. J. S. Dewar, T. Mole, D. S. Urch, and E. W. T. Warford . . . 3572

690. Electrophilic Substitution. Part V. Competitive Nitrations.
By M. J. S. Dewar, T. Mole, and E. W. T. Warford 3576

691. Electrophilic Substitution. Part VI. The Nitration of Aromatic Hydrocarbons; Partial Rate Factors and their Interpretation.
By M. J. S. Dewar, T. Mole, and E. W. T. Warford 3581

694. *peri*-Hydroxycarbonyl Compounds. Part II. The Effect of Ring Size on Hydrogen Bonding.
By V. C. Farmer, N. F. Hayes, and R. H. Thomson 3600

695. Lactones. Part III. A Further Example of Alkyl–Oxygen Bond Fission in Phthalide Ring Opening.
By John Blair, W. R. Logan, and G. T. Newbold 3608

700. Fluorine-substituted Polycyclic Compounds.
By G. M. Badger and J. F. Stephens 3637

701. The Formation of *iso*But-1-enyl Radicals from *iso*But-1-enylsilver. Part II.
By F. Glockling 3640

702. Polypeptides. Part IV. The Self-condensation of the Esters of Some Peptides of Glycine and Proline.
By H. N. Rydon and P. W. G. Smith 3642

704. The Structure of N_β-Alkyl-β-carboline Anhydro-bases.
By Ian D. Spenser 3659

705. Synthesis of Heterocyclic Compounds from δ-Unsaturated 1 : 3-Diketo-esters.
By Gabra Soliman and Latif Rateb 3663

706. Diaryl-2 : 2′-disulphonic Acids and Related Compounds. Part II. The Optical Stability of a Cyclic 2 : 2′-Thiolsulphonate.
By W. L. F. Armarego and E. E. Turner 3668

Notes:

707. The Racemisation of 9 : 10-Dihydro-3 : 4-5 : 6-dibenzophenanthrene.
By D. Muriel Hall 3674

709. Absorption Spectra of Ketones. Part V. γ-Substituted αβ-Unsaturated Ketones.
By C. W. Bird, R. C. Cookson, and S. H. Dandegaonker 3675

710. Synthesis of Tetramethylhydrazine by Photolysis and Pyrolysis of Tetramethyltetrazen.
By J. S. Watson 3677

711. The Preparation of the Half Esters of Phthalic Acid and of 3-Nitrophthalic Acid.
By M. K. Hargreaves 3679

PAGE

713. Bitter Principles of the Cucurbitaceae. Part IV. Dehydrogenation of Cucurbitacin A.
By P. R. Enslin and D. E. A. Rivett 3682

714. Further Substitution in 5-Substituted Benziminazoles.
By R. D. Brown and M. L. Heffernan 3683

715. Some Derivatives of 4-Propylpyridine and 5 : 6-Benzoquinoline.
By C. W. Rees 3684

716. The Janovsky Reaction.
By M. J. Newlands and F. Wild 3686

Tilden Lecture:

Recent Progress in the Chemistry of Peptides.
By G. W. Kenner 3689

INDEX OF AUTHORS' NAMES.

Aitken, I. M., and Reid, D. H., 3487.
Alcock, K. See Dawson, J. K., 3531.
Alles, B. J. P., and Sultanbawa, M. U. S., 3472.
Armarego, W. L. F., and Turner, E. E., 3668.
Aspinall, G. O., Jamieson, R. S. P., and Wilkinson, J. F., 3483.
Bader, H., 3293.
Badger, G. M., and Christie, B. J., 3435, 3438.
Badger, G. M., and Stephens, J. F., 3637.
Bagnall, K. W., D'Eye, R. W. M., and Freeman, J. H., 3385.
Barr, D. A., and Haszeldine, R. N., 3416, 3428.
Barrer, R. M., and Stuart, W. I., 3307.
Barry, V. C., Belton, J. G., O'Sullivan, J. F., and Twomey, D., 3347.
Bartlett, B. E., Tompkins, F. C., and Young, D. A., 3323.
Barton, D. H. R., Campos-Neves, A. da S., and Cookson, R. C., 3500.
Beer, R. J. S., Hanson, K. R., and Robertson, A., 3280.
Belton, J. G. See Barry, V. C., 3347.
Bevington, J. C., and Ghanem, N. A., 3506.
Bircumshaw, L. L. See Tayler, F. M., 3405.
Bird, C. W., Cookson, R. C., and Dandegaonker, S. H., 3675.
Blair, J., Logan, W. R., and Newbold, G. T., 3608.
Booth, G. C., and Gold, V., 3380.
Bradley, D. C., Chatterjee, A. K., and Wardlaw, W., 3469.
Braude, E. A., and Evans, E. A., 3333.
Brown, D. J., and Mason, S. F., 3443.
Brown, R. D., and Heffernan, M. L., 3683.
Campbell, R., and Robinson, P. L., 3454.
Campos-Neves, A. da S. See Barton, D. H. R., 3500.
Carbarns, T. See Gordon, M., 3298.
Carrington, A., and Symons, M. C. R., 3373.
Chan, W. R., and Hassall, C. H., 3495.
Chatterjee, A. K. See Bradley, D. C., 3469.
Chilton, D. R. See Dawson, J. K., 3531.
Christie, B. J. See Badger, G. M., 3435, 3438.
Clemo, G. R., Raper, R., and Seaton, J. C., 3390.
Coates, G. E., and Whitcombe, R. A., 3351.
Cookson, R. C. See Barton, D. H. R., 3500, and Bird, C. W., 3675.
Coulson, C. A., and Lester, G. R., 3650.
Cumper, C. W. N., Vogel, A. I., and Walker, S., 3621.
Dailly, D. F., and Elliott, T. A., 3398.
Dandegaonker, S. H. See Bird, C. W., 3675.
Davies, A. G., Kenyon, J., and Thaker, K., 3394.
Dawson, J. K., Wait, E., Alcock, K., and Chilton, D. R., 3531.
Dean, F. M., Erni, A. D. T., and Robertson, A., 3545.
D'Eye, R. W. M. See Bagnall, K. W., 3385.
de la Mare, P. B. D., Leffek, K., and Salama, A., 3686.
de la Mare, P. B. D., and Salama, A., 3337.
Dewar, M. J. S., Mole, T., Urch, D. S., and Warford, E. W. T., 3572.
Dewar, M. J. S., Mole, T., and Warford, E. W. T., 3576, 3581.
Dewar, M. J. S., and Warford, E. W. T., 3570.
Duff, D. J., 3296.
Duncan, J. F., and Lynn, K. R., 3512, 3519, 3674.
Elliott, T. A. See Dailly, D. F., 3398.
Enslin, P. R., and Rivett, D. E. A., 3682.
Erni, A. D. T. See Dean, F. M., 3545.
Evans, E. A. See Braude, E. A., 3333.
Farmer, V. C., Hayes, N. F., and Thomson, R. H., 3600.
Fidler, W. E., and Wood, H. C. S., 3311.
Flitcroft, T., and Skinner, H. A., 3355.
Forrest, J., Hansen, S. B., and Petrow, V., 3541.
Freeman, J. H. See Bagnall, K. W., 3385.
Garden, J. F., Hayes, N. F., and Thomson, R. H., 3315.
Gerrard, W., Lappert, M. F., and Silver, H. B., 3285.
Ghanem, N. A. See Bevington, J. C., 3506.
Gilmour, A. See Nelson, S. M., 3463.
Glockling, F., 3640.
Gold, V. See Booth, G. C., 3380.
Goodman, J. F., and Gregg, S. J., 3612.
Goodwin, T. H., and Porte, A. L., 3595.
Gordon, M., and Carbarns, T., 3298.
Gregg, S. J. See Goodman, J. F., 3612.
Hall, D. M., 3674.
Hall, D. M., Ladbury, J. E., Lesslie, M. S., and Turner, E. E., 3476.
Hamilton, W. See Lawrie, W., 3272.
Hamor, T. A., and Robertson, J. M., 3586.
Hansen, S. B. See Forrest, J., 3541.
Hanson, K. R. See Beer, R. J. S., 3280.
Hargreaves, M. K., 3679.
Harvey, G. J., and Stimson, V. R., 3629.

Hassall, C. H. See Chan, W. R., **3495**.
Haszeldine, R. N., and West, B. O., **3631**.
Haszeldine, R. N. See also Barr, D. A., **3416**, **3428**.
Hayes, N. F. See Farmer, V. C., **3600**, and Garden, J. F., **3315**.
Heffernan, M. L. See Brown, R. D., **3683**.
Henbest, H. B., and Wilson, R. A. L., **3289**.
Hetherington, G., and Robinson, P. L., **3681**.
Hudson, R. F., and Keay, L., **3269**.
Iengar, H. V. R., and Ritchie, P. D., **3563**.
Jamieson, R. S. P. See Aspinall, G. O., **3483**.
Keay, L. See Hudson, R. F., **3269**.
Kenner, G. W., **3689**.
Kenner, G. W., and Mather, J., **3524**.
Kenyon, J. See Davies, A. G., **3394**.
Ladbury, J. E. See Hall, D. M., **3475**.
Lappert, M. F. See Gerrard, W., **3285**.
Lawrie, W., Hamilton, W., Spring, F. S., and Watson, H. S., **3272**.
Le Fèvre, C. G., and Le Fèvre, R. J. W., **3549**.
Le Fèvre, R. J. W. See Le Fèvre, C. G., **3549**.
Leffek, K. See de la Mare, P. B. D., **3686**.
Lesslie, M. S. See Hall, D. M., **3475**.
Lester, G. R. See Coulson, C. A., **3650**.
Logan, W. R. See Blair, J., **3608**.
Long, L. H., **3410**.
Lynn, K. R. See Duncan, J. F., **3512**, **3519**, **3674**.
Mason, S. F. See Brown, D. J., **3443**.
Mather, J. See Kenner, G. W., **3524**.
Michelson, A. M., and Todd, Sir A., **3459**.
Mole, T. See Dewar, M. J. S., **3572**, **3576**, **3581**.
Nelson, S. M., Gilmour, A., and Pink, R. C., **3463**.
Newbold, G. T. See Blair, J., **3608**.
Newlands, M. J., and Wild, F., **3686**.
Ockenden, D. W., and Welch, G. A., **3358**.
O'Sullivan, J. F. See Barry, V. C., **3347**.
Petrow, V. See Forrest, J., **3541**.
Pink, R. C. See Nelson, S. M., **3463**.
Porte, A. L. See Goodwin, T. H., **3595**.
Raper, R. See Clemo, G. R., **3390**.
Rateb, L. See Soliman, G., **3663**.
Rees, C. W., **3684**.
Reichenberg, D., and Wall, W. F., **3364**.
Reid, D. H. See Aitken, I. M., **3487**.
Ritchie, P. D. See Iengar, H. V. R., **3563**.
Rivett, D. E. A. See Enslin, P. R., **3682**.
Robertson, A. See Beer, R. J. S., **3280**, and Dean, F. M., **3545**.
Robertson, J. M. See Hamor, T. A., **3586**.
Robins, P. A., and Walker, J., **3249**, **3260**.
Robinson, P. L. See Campbell, R., **3454**, and Hetherington, G., **3681**.
Rodda, H. J., **3509**.
Rydon, H. N., and Smith, P. W. G., **3642**.
Salama, A. See de la Mare, P. B. D., **3337**, **3686**.
Seaton, J. C. See Clemo, G. R., **3390**.
Silver, H. B. See Gerrard, W., **3285**.
Skinner, H. A. See Flitcroft, T., **3355**.
Smith, P. W. G. See Rydon, H. N., **3642**.
Soliman, G., and Rateb, L., **3663**.
Spenser, I. D., **3659**.
Spice, J. E., and Twist, W., **3319**.
Spring, F. S. See Lawrie, W., **3272**.
Stephens, J. F. See Badger, G. M., **3637**.
Stimson, V. R. See Harvey, G. J., **3629**.
Stuart, W. I. See Barrer, R. M., **3307**.
Sultanbawa, M. U. S. See Alles, B. J. P., **3472**.
Symons, M. C. R. See Carrington, A., **3373**.
Tayler, F. M., and Bircumshaw, L. L., **3405**.
Thaker, K. See Davies, A. G., **3394**.
Thomson, R. H. See Farmer, V. C., **3600**, and Garden, J. F., **3315**.
Todd, Sir A. See Michelson, A. M., **3459**.
Tompkins, F. C., and Young, D. A., **3331**.
Tompkins, F. C. See also Bartlett, B. E., **3323**.
Turner, E. E. See Armarego, W. L. F., **3668**, and Hall, D. M., **3475**.
Twist, W. See Spice, J. E., **3319**.
Twomey, D. See Barry, V. C., **3347**.
Urch, D. S. See Dewar, M. J. S., **3572**.
Vogel, A. I. See Cumper, C. W. N., **3621**.
Wait, E. See Dawson, J. K., **3531**.
Walker, J. See Robins, P. A., **3249**, **3260**.
Walker, S. See Cumper, C. W. N., **3621**.
Wall, W. F. See Reichenberg, D., **3364**.
Wardlaw, W. See Bradley, D. C., **3469**.
Warford, E. W. T. See Dewar, M. J. S., **3570**, **3572**, **3576**, **3581**.
Watson, H. S. See Lawrie, W., **3272**.
Watson, J. S., **3677**.
Welch, G. A. See Ockenden, D. W., **3358**.
West, B. O. See Haszeldine, R. N., **3631**.
Whitcombe, R. A. See Coates, G. E., **3351**.
Wild, F. See Newlands, M. J., **3686**.
Wilkinson, J. F. See Aspinall, G. O., **3483**.
Wilson, R. A. L. See Henbest, H. B., **3289**.
Wood, H. C. S. See Fidler, W. E., **3311**.
Young, D. A. See Bartlett, B. E., **3323**, and Tompkins, F. C., **3331**.

A brochure describing the activities of the Society and forms of application for Fellowship can be obtained from The General Secretary, The Chemical Society, Burlington House, Piccadilly, London, W.1.

Authors are requested to see that their papers conform as nearly as possible to the normal conventions of the *Journal* and should consult the brochure entitled "The Presentation of Papers for the *Journal* of the Chemical Society," which may be obtained from the General Secretary.

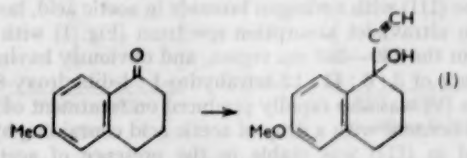
Attention is also drawn to changes in the method of quoting references (cf. *Proceedings*, July, 1955, 79).

632. *Studies on the Diels–Alder Reaction. Part IV.* Reduction Products of* cis-syn-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Octahydro-8-methoxy-*1 : 4-*dioxochrysene and their Interrelation.*

By P. A. Robins and James Walker.

1-Ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene (I), derived from the tetralone (II), has been converted by partial hydrogenation and dehydration into 3 : 4-dihydro-6-methoxy-1-vinylnaphthalene, which, on addition of *p*-benzoquinone, afforded *cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-octahydro-8-methoxy-1 : 4-dioxochrysene (III). Partial reductions and stereochemical transformations of the type previously applied in the hydrophenanthrene series [1a, b] have been applied to this compound, and the structures of the products are demonstrated.

The work described in the present communication was carried out in the course of extending our previous study [1] of perhydro-1 : 4-dioxophenanthrenes and related compounds to the chrysene series. For this purpose it was fortunate that a recent patent [2] has reported that 1-ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene (I) is obtainable in good yield by the reaction between 1 : 2 : 3 : 4-tetrahydro-6-methoxy-1-oxonaphthalene (II) and lithium acetylide in liquid ammonia at room temperature in a sealed vessel. Previous attempts to prepare the acetylenic alcohol (I) by reaction between the tetralone (II) and sodium or potassium acetylide have failed,[3] or have given moderate yields only,[4] while the use of ethynylmagnesium bromide [5, 6] has allowed the preparation of small quantities of impure material to be undertaken with great experimental difficulty, and the formation of considerable amounts of disubstituted acetylene, >C(OH)·C≡C·C(OH)< or >C·C≡C·C<, was also reported.[3, 5, 6] Using the lithium acetylide method we have been able to obtain consistent net yields of over 60% of the acetylenic alcohol (I) by careful attention to experimental detail, in particular by



ensuring the presence of a large excess of acetylene during the reaction stage at room temperature, the product being obtained crystalline. Previous workers [5, 6] who prepared this compound by the ethynylmagnesium bromide method found either that their crude products underwent spontaneous partial dehydration to the enyne or that distillation gave a partially dehydrated product with occasional polymerisation, and a similar result was reported for a preparation employing sodium acetylide in dioxan at 30—40°.[4a] We have found in contrast to these reports, and in agreement with Goldberg and Scott,[2] that the solid acetylenic alcohol (I) can be distilled unchanged, even at water-pump vacua (b. p. *ca.* 180°/15 mm.). Dehydration by chemical methods occurs readily but in most cases

* Part III, *J.*, 1954, 3960.

[1] Robins and Walker, (*a*) *J.*, 1952, 642; (*b*) 1954, 3960; (*c*) 1955, 1789; (*d*) *Chem. and Ind.*, 1955, 772.

[2] Goldberg and Scott, U.S.P. 2,524,787.

[3] Birch and Robinson, *J.*, 1944, 503.

[4] Breitner, (*a*) in "Pharmaceuticals at the I.G. Farbenindustrie Plant, Elberfeld, Germany," C.I.O.S. Report, Item 24, File XXV—54, p. 20 (35% yield); (*b*) *Medizin und Chemie*, 1942, **4**, 317; (*c*) Wunderlich, Dissertation, Wurzburg, 1939, quoted by Buchta and Bayer, *Annalen*, 1953, **580**, 117.

[5] (*a*) Dane, Höss, Bindseil, and Schmitt, *Annalen*, 1937, **532**, 39; (*b*) Dane, Höss, Eder, Schmitt, and Schön, *ibid.*, 1938, **536**, 183.

[6] (*a*) Goldberg and Müller, *Helv. Chim. Acta*, 1940, **23**, 831; (*b*) Bachmann and Chemerda, *J. Amer. Chem. Soc.*, 1948, **70**, 1468; (*c*) Bachmann and Controulis, *ibid.*, 1951, **73**, 2636; (*d*) Nazarov and Kotlyarevskii, *Bull. Acad. Sci. U.S.S.R.* (*Sect. Chem. Sci.*), 1953, 1100.

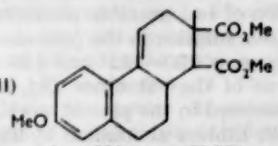
rapid polymerisation of the resulting product takes place. The Hibbert method,[7] employing iodine in boiling benzene, failed; the use either of thionyl chloride or of phosphoryl chloride in pyridine resulted in a violent reaction and the production of resin; toluene-*p*-sulphonic acid or anhydrous oxalic acid in boiling benzene, or acetic anhydride–sulphuric acid gave only tars. The use of acetic anhydride under reflux[4a] was also unsatisfactory. Alone among the methods employed, rapid distillation on a small scale from fused potassium hydrogen sulphate gave an oil, which, on subsequent partial hydrogenation and reaction with *p*-benzoquinone, gave a quantity of the chrysene derivative (III) indicating that the initial dehydration had given at least 60% of 1-ethynyl-3 : 4-dihydro-6-methoxynaphthalene.

Alternatively, partial hydrogenation of the acetylenic alcohol (I) with the Lindlar[8] lead-poisoned palladised calcium carbonate catalyst gave smoothly 1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxy-1-vinylnaphthalene, which could be distilled in small quantities without undergoing dehydration. Attempted dehydration under acid conditions gave only polymeric material, but, in this instance, the Hibbert method[7] was successful when a basic polymerisation-inhibitor, such as quinoline or phenyl-β-naphthylamine, was present. Attempts to isolate the resulting 3 : 4-dihydro-6-methoxy-1-vinylnaphthalene indicated that it readily polymerised,[9] and it was best allowed to react directly in benzene solution at room temperature with *p*-benzoquinone to give the desired *cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-octahydro-8-methoxy-1 : 4-dioxochrysene (III) in 70% yield [based on the acetylenic alcohol (I)]; this substance (III) has been prepared by Dane *et al.*[5] in unspecified yield, but it has not previously been studied in detail.

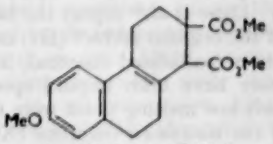
The *cis-syn*-configuration is assigned to the compound (III) on the basis of the Alder–Stein[10] rules for diene additions. When it (III) was cautiously treated under nitrogen with alcoholic alkali, aromatisation of the ring containing the two carbonyl groups took place and the product, 5 : 6 : 12 : 15-tetrahydro-1 : 4-dihydroxy-8-methoxychrysene (IV), showed in its ultraviolet absorption spectrum (Fig. 1) two bands characteristic of the two isolated chromophores—one at 265 mμ, characteristic of a methoxystyrene chromophore of the type incorporated in (IV) (see below), and a typical quinol band at 295 mμ. Treatment of the diketone (III) with hydrogen bromide in acetic acid, however, gave an isomeric structure having an ultraviolet absorption spectrum (Fig. 1) with a broad band showing signs of resolution in the 330—340 mμ region, and obviously having the conjugated *trans*-stilbene-like structure of 5 : 6 : 11 : 12-tetrahydro-1 : 4-dihydroxy-8-methoxychrysene (V). The same substance (V) was also rapidly produced on treatment of the alkali-isomerisation product (IV) in hot benzene with a drop of acetic acid containing hydrogen bromide. The 11 : 16-double bond in (III) was stable in the presence of acetic acid, and reduction of (III) with zinc and acetic acid removed the 2 : 3-double bond to give *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (VI) showing a maximum in its ultraviolet absorption spectrum at 264 mμ (Fig. 2). The 11 : 16-double bond in (VI), however, was labile in presence of mineral acid and readily migrated into the 15 : 16-position to give *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-8-methoxy-1 : 4-dioxochrysene (VII), showing a maximum in its ultraviolet absorption spectrum at 273·5 mμ (Fig. 2), the shift in the position of maximum absorption being accompanied by a slight drop in the extinction coefficient. The position of the maximum observed for this compound (VII) agrees well with other data reported for 3 : 4-dihydro-6-methoxynaphthalenes,[11] and, in particular, the shift in the position of maximum absorption to longer wavelength in passing from (VI) to (VII) is in accord with previous experience of analogous structures,[11b,d] especially with the observations of Heer and Miescher[11b] on the change in ultraviolet light absorption in passing from (VIII) to (IX). Although the shift is small the position of maximum absorption in this group of substances is diagnostic of the position

[7] Hibbert, *J. Amer. Chem. Soc.*, 1915, **37**, 1748.
[8] Lindlar, *Helv. Chim. Acta*, 1952, **35**, 440.
[9] Cf. Buchta and Bayer, *Annalen*, 1953, **580**, 116.
[10] Alder and Stein, *Angew. Chem.*, 1937, **50**, 510.
[11] (*a*) Woodward and Eastman, *J. Amer. Chem. Soc.*, 1944, **66**, 674; (*b*) Heer and Miescher, *Helv. Chim. Acta*, 1948, **31**, 219; (*c*) Hogg, *J. Amer. Chem. Soc.*, 1949, **71**, 1918; (*d*) Juday, *ibid.*, 1953, **75**, 3008.

of the olefinic double bond, as further examples will show later; it does not, of course, apply when the methoxystyrene chromophore is conjugated with another chromophore,



(VIII) $\lambda_{max.}$ 264 mμ; ε 20,900



(IX) $\lambda_{max.}$ 275 mμ; ε 18,500

as in (V) (above). During the acid isomerisation of (VI) to (VII) in ethanolic hydrochloric acid, the formation of a by-product $C_{21}H_{22}O_2$ in about 20% yield was observed, and with methanolic hydrochloric acid a similar by-product $C_{20}H_{20}O_2$, containing two methoxyl

FIG. 1.

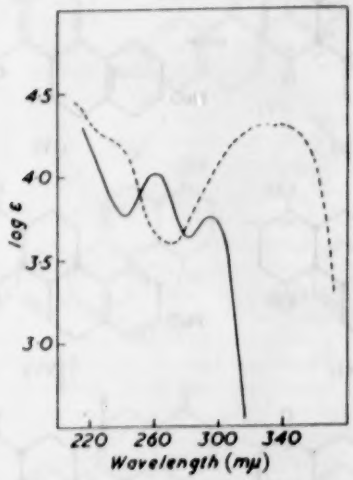


FIG. 2.

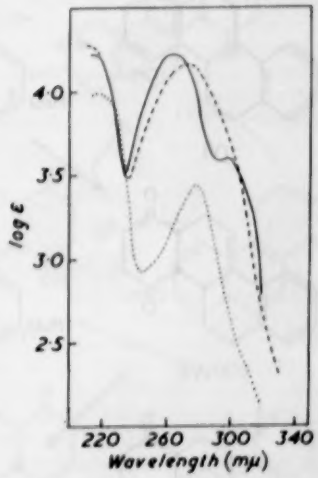


FIG. 1. *Ultraviolet light absorption of* 5 : 6 : 12 : 15-*tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (IV) (——), *and* 5 : 6 : 11 : 12-*tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (V) (– – –).

FIG. 2. *Ultraviolet light absorption of* cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VI) (——), cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VII) (– – –), *and* cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*dodecahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (X) (· · ·).

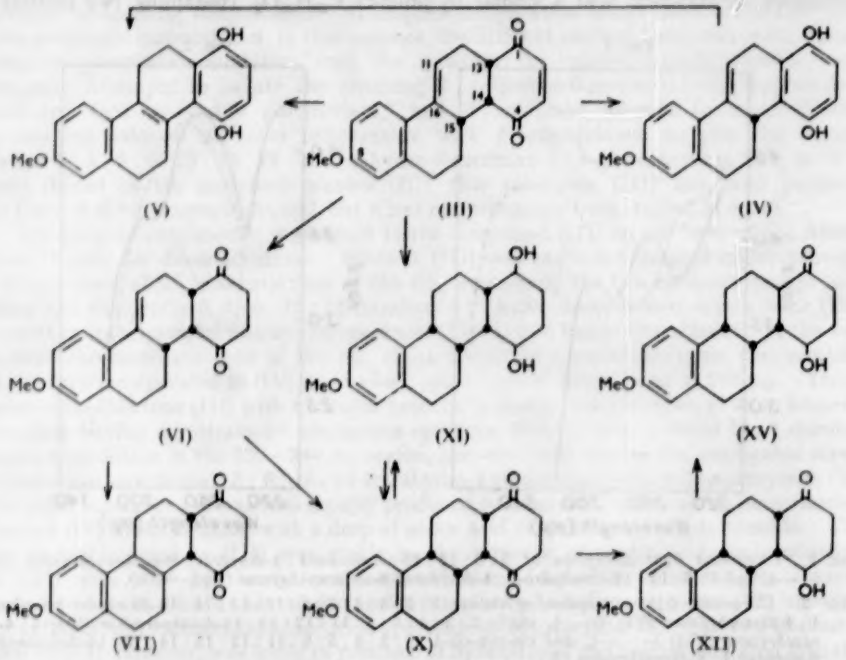
groups, was obtained. The ultraviolet light absorption characteristics of these two substances were virtually indistinguishable and indicated that a radical change in structure had occurred. The two methoxyl groups in the latter compound accounted for the two oxygen atoms, and the substances were obviously derived from (VI), or from (VII), by the loss of the elements of two molecules of water and the addition of the elements of the alcohol employed. The structures and mode of formation of these compounds will be discussed in the following paper.

The *cis-syn*-diketone (VI) on catalytic hydrogenation in the presence of palladised strontium carbonate took up one mol. of hydrogen to give *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-8-methoxy-1 : 4-dioxochrysene (X), since catalyst hindrance [12] would have effectively prevented the formation of the alternative *cis-syn-trans*-structure, and this substance (X) proved to be rather unstable to heat, partly decomposing to a yellow gum on crystallisation from hot solvents. By keeping the

[12] Linstead, Doering, Davis, Levine, and Whetstone, *J. Amer. Chem. Soc.*, 1942, **64**, 1985.

time of heating to a minimum or by recrystallisation in the cold by the slow addition of light petroleum to a chloroform solution of the compound, it could be obtained in the form of prisms, m. p. 159—164° (decomp.); the ultraviolet light absorption (Fig. 2) was of the anisole type. Dane *et al.*[5b] report the isolation of two unstable products on catalytic hydrogenation of the original adduct (III) in anisole solution in the presence of palladised calcium carbonate or palladised charcoal, having m. p. 130—132° and 145—148° respectively. These may have been impure specimens of the substance (X), since no pure compounds of such low melting point were encountered in the present work.

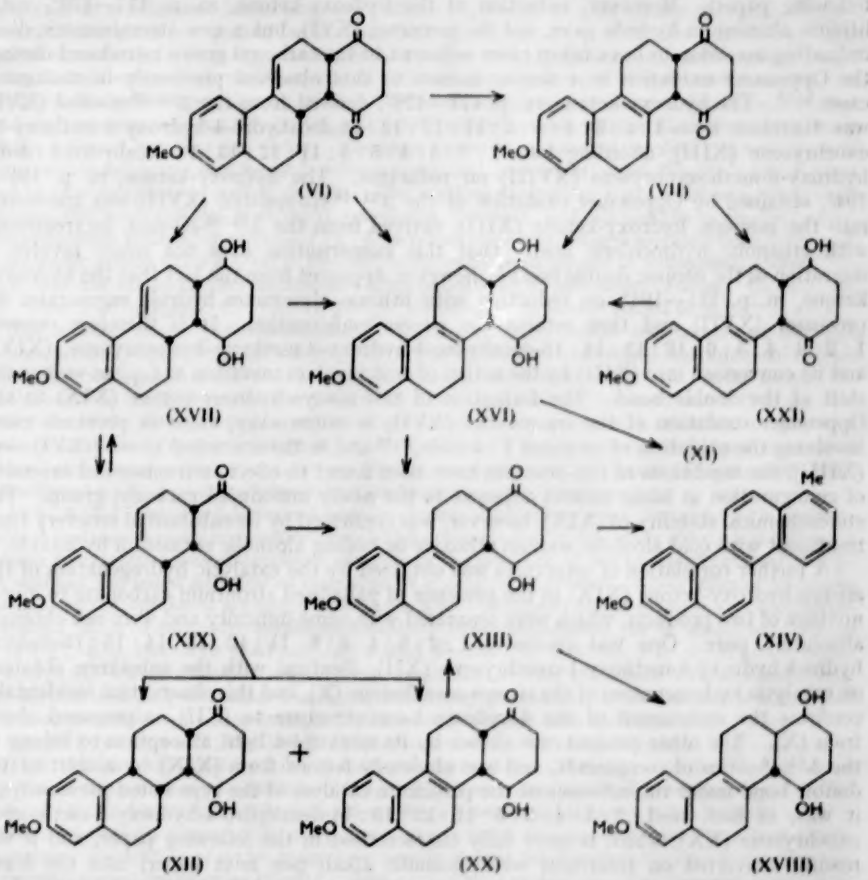
Reduction of the *cis-syn-cis*-diketone (X) with lithium aluminium hydride afforded a *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-1 : 4-dihydroxy-8-methoxychrysene (XI), identical with the diol obtained directly by catalytic hydrogenation of the original adduct (III) in glacial acetic acid in the presence of Adams's platinum oxide



catalyst, thus indicating the stereochemical course of the reduction of the carbonyl groups to be the same in both cases. This diol (XI) showed a double melting point at 158—161° and 170—173°, and was probably identical with the dihydroxy-compound, m. p. 163°, reported by Dane *et al.*[5b] from a similar catalytic reduction of the adduct (III). The products, allegedly formed by reductive demethoxylation, of m. p. 194° and 183—184° obtained by Dane *et al.*[5b] on catalytic hydrogenation of (III) with platinum in acetic acid and anisole respectively were not encountered during the present investigation. Catalytic hydrogenation of the *cis-syn-cis*-diketone (X) in ethyl acetate in the presence of Adams's platinum oxide catalyst resulted in the uptake of one mol. of hydrogen and production of a hydroxy-ketone. On the basis of experience in the perhydrophenanthrene series[1a,b] this substance should have been *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-4-hydroxy-8-methoxy-1-oxochrysene (XII), and this structure was subsequently proved (see below) by correlation of (XII) with a hydroxy-ketone (XIII) which was converted into 8-methoxy-1-methylchrysene (XIV). The *cis-syn-cis*-hydroxy-ketone (XII) was stereochemically unstable and was readily converted on treatment with alcoholic

alkali into the more stable *trans-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-4-hydroxy-8-methoxy-1-oxochrysene (XV). [cf. 1a, b]

Reduction of the *cis-syn*-diketone (VI) with lithium aluminium hydride afforded two alternative products according to the experimental conditions. Reduction under vigorous conditions in boiling tetrahydrofuran, followed by decomposition of the reaction mixture with water and mineral acid, gave a diol of m. p. 152—156°. As the same substance was obtained by reduction of the *cis*-diketone (VII) with lithium aluminium hydride and as it showed a maximum in its ultraviolet light absorption at 273 mμ, it must have had the olefinic double bond in the 15 : 16-position and was therefore *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1 : 4-dihydroxy-8-methoxychrysene (XVI); it passed into the *cis-syn-cis*-diol (XI), showing the characteristic double melting point described above, on catalytic hydrogenation in acetic acid in presence of Adams's platinum



oxide catalyst. On the other hand reduction of the *cis-syn*-diketone (VI) with lithium aluminium hydride in cold tetrahydrofuran (or with but a brief period of heating) followed by a working-up procedure not involving the use of acid gave a diol, isomeric with (XVI), of m. p. 183—185°; it showed a maximum in its ultraviolet light absorption at 265 mμ and was obviously *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-1 : 4-dihydroxy-8-methoxychrysene (XVII). The olefinic double bond in the 11 : 16-position in this substance (XVII), as in other instances noted above, was labile in presence of mineral acid, and brief

treatment of (XVII) with alcoholic hydrochloric acid effected complete conversion into the isomeric $\Delta^{15:16}$-*cis*-diol (XVI).

Partial oxidation of either the $\Delta^{15:16}$-*cis*-diol (XVI) or the $\Delta^{11:16}$-*cis-syn*-diol (XVII) with the chromium trioxide–pyridine reagent [15,13] failed to give any recognisable product other than some unchanged starting material, but Oppenauer oxidation gave in each case a hydroxy-ketone with retention of the original position of the olefinic double bond as shown by the ultraviolet light absorption. The carbonyl group introduced by the Oppenauer reaction should, by analogy with experience in the hydrophenanthrene series,[15] be at $C_{(1)}$, and confirmation of this was obtained by marking the position of the carbonyl group in the hydroxy-ketone, m. p. 177—179°, derived from the $\Delta^{15:16}$-*cis*-diol (XVI), with methylmagnesium iodide, followed by dehydration and dehydrogenation to give 8-methoxy-1-methylchrysene (XIV), identical with an authentic synthetic specimen (see following paper). Moreover, reduction of the hydroxy-ketone, m. p. 177—179°, with lithium aluminium hydride gave, not its precursor (XVI), but a new stereoisomeric diol, indicating inversion to have taken place adjacent to the carbonyl group introduced during the Oppenauer oxidation in a similar fashion to that observed previously in analogous cases.[15,13] The hydroxy-ketone, m. p. 177—179°, derived from the $\Delta^{15:16}$-*cis*-diol (XVI) was therefore *trans*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XIII), affording *trans*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1 : 4-dihydroxy-8-methoxychrysene (XVIII) on reduction. The hydroxy-ketone, m. p. 191—194°, obtained by Oppenauer oxidation of the $\Delta^{11:16}$-*cis-syn*-diol (XVII) was converted into the isomeric hydroxy-ketone (XIII), derived from the $\Delta^{15:16}$-*cis*-diol, by treatment with ethanolic hydrochloric acid. That this isomerisation does not solely involve a migration of the olefinic double bond is, however, apparent from the fact that the hydroxy-ketone, m. p. 191—194°, on reduction with lithium aluminium hydride regenerates its precursor (XVII) and thus retains the *cis-syn*-configuration. It is therefore *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XIX), and its conversion into (XIII) by the action of acid involves inversion at $C_{(13)}$ as well as the shift of the double bond. The formation of this *cis-syn*-hydroxy-ketone (XIX) in the Oppenauer oxidation of the *cis-syn*-diol (XVII) is noteworthy, since in previous cases involving the oxidation of *cis*-fused 1 : 4-diols,[15,13] and in the one noted above [(XVI) ⟶ (XIII)], the conditions of this reaction have been found to effect stereochemical inversion of configuration at labile centres adjacent to the newly introduced carbonyl group. The stereochemical stability of (XIX), however, was confirmed by its substantial recovery from treatment with cold alcoholic sodium ethoxide or boiling alcoholic potassium hydroxide.

A further correlation of structures was obtained by the catalytic hydrogenation of the *cis-syn*-hydroxy-ketone (XIX) in the presence of palladised strontium carbonate to give a mixture of two products, which were separated with some difficulty and were not obtained absolutely pure. One was *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-4-hydroxy-8-methoxy-1-oxochrysene (XII), identical with the substance obtained on catalytic hydrogenation of the *cis-syn-cis*-diketone (X), and this observation incidentally confirms the assignment of the 4-hydroxy-1-oxo-structure to (XII) as prepared above from (X). The other product was shown by its ultraviolet light absorption to belong to the $\Delta^{15:16}$-series of compounds, and was obviously formed from (XIX) by a shift of the double bond under the influence of the palladium catalyst of the type noted previously ;[15] it was, in fact, *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XX), which is more fully characterised in the following paper, and it was readily converted on treatment with alcoholic alkali (see next paper) into the *trans*-compound (XIII). A new $\Delta^{15:16}$-hydroxy-ketone, m. p. 167—168°, was obtained on catalytic hydrogenation of the $\Delta^{15:16}$-*cis*-diketone (VII) in the presence of palladised strontium carbonate. As it could be further reduced with lithium aluminium hydride to give the $\Delta^{15:16}$-*cis*-diol (XVI), and since it differed from the $\Delta^{15:16}$-*cis*-hydroxy-ketone (XX) but nevertheless contained the hydroxyl group in the same absolute configuration as one of those present in (XVI), it must have been the isomeric *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1-hydroxy-8-methoxy-4-oxochrysene (XXI).

[15] Poos, Arth, Beyler, and Sarett, *ibid.*, 1953, **75**, 422.

It decomposed when heated with alcoholic alkali in an attempt to convert it into the *trans*-stereoisomer, but it was stable to adsorption on to, and desorption from, alkaline alumina. Treatment with perchloric acid in ethyl acetate, previously used [1b] with success for the stereochemical equilibration of diketones in the hydrophenanthrene series, merely gave the acetate of (XXI).

Experimental

M. p.s given in the form " m. p. (micro) " were observed on a microscope hot stage, otherwise they were taken in capillary tubes in the usual way. Ultraviolet light absorption measurements were made in 96% EtOH unless otherwise stated. Light petroleum refers to the fraction of boiling range 60—80°.

1-Ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene (I) (cf. ref. 2).—A solution of lithium acetylide (from 3·82 g. of lithium) in liquid ammonia (*ca.* 800 c.c.) was transferred to the glass liner of a mild-steel bomb (capacity, 1700 c.c.), cooled in solid carbon dioxide. A rapid stream of acetylene was passed for 20 min., and then 1 : 2 : 3 : 4-tetrahydro-6-methoxy-1-oxonaphthalene (44 g., 0·25 mole) was added as powder. The glass liner was immediately placed in the chilled bomb which was then sealed. After warming to room temperature the bomb was rotated in an inclined position for 20 hr. Excess of acetylene and ammonia were then vented, the bomb was opened, and the brown pasty residue was treated with solid ammonium chloride (30 g.), followed by ether and water. The ether layer was separated, washed successively with water, dilute sulphuric acid (until free from ammonia), and water, dried (Na_2SO_4), and evaporated in an atmosphere of carbon dioxide. The residual dark oil, or pasty solid, was taken up in benzene (50 c.c.), diluted with light petroleum (50 c.c.), and allowed to crystallise at 0°. Filtration then afforded 1-ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene (I) as brownish prisms (24·5 g.), m. p. 88—89°, sufficiently pure for use in subsequent stages; the m. p. was not raised on recrystallisation from benzene–light petroleum (Found : C, 77·3; H, 7·1. Calc. for $C_{13}H_{14}O_2$: C, 77·2; H, 7·0%). Goldberg and Scott [2] record m. p. 89°.

The mother-liquors were evaporated to dryness and the residue was treated at 50° with semicarbazide (from 20 g. of semicarbazide hydrochloride neutralised by aqueous sodium hydroxide) and acetic acid (1 c.c.) in 85% aqueous methanol (400 c.c.). After 20 hr. the precipitated 1 : 2 : 3 : 4-tetrahydro-6-methoxy-1-oxonaphthalene semicarbazone (7·6 g.) was collected and the filtrate was poured into much water. Extraction with ether and evaporation of the washed and dried extract gave an oily residue (7·7 g.), which was dissolved in benzene (10 c.c.) and diluted with light petroleum (10 c.c.) to yield a further crop (3·6 g.; m. p. 86—88°) of 1-ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene.

1 : 2 : 3 : 4-Tetrahydro-1-hydroxy-6-methoxy-1-vinylnaphthalene.—1-Ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene (5·75 g.) was shaken in dry ether (50 c.c.) in hydrogen at room temperature and atmospheric pressure in the presence of the Lindlar [3] catalyst (0·2 g.) but without the usual addition of quinoline as a catalyst inhibitor. Absorption of hydrogen ceased after the uptake of approx. 1 mol. in *ca.* 4 hr. Removal of the catalyst and distillation afforded 1 : 2 : 3 : 4-*tetrahydro*-1-*hydroxy*-6-*methoxy*-1-*vinylnaphthalene* as a colourless viscous oil (5·4 g.), b. p. 106—110°/0·01 mm., n_D^{23} 1·5648 (Found : C, 76·8; H, 7·7. $C_{15}H_{16}O_2$ requires C, 76·5; H, 7·9%). Distillation of large quantities of this substance was unsatisfactory, dehydration and polymerisation frequently occurring, particularly when an acid washing had been used to remove quinoline in experiments in which it had been included.

cis-syn-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Octahydro-8-methoxy-1 : 4-dioxochrysene (III).—1-Ethynyl-1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxynaphthalene (25·9 g.) was hydrogenated as above with the addition of quinoline (0·2 c.c.) which was not removed subsequently, and the crude 1 : 2 : 3 : 4-tetrahydro-1-hydroxy-6-methoxy-1-vinylnaphthalene was heated with a crystal of iodine in benzene (80 c.c.) under reflux with the conventional Dean and Stark apparatus. Separation of water took place rapidly during the first few minutes of heating and practically ceased in 20 min. (Found : 2·05 c.c. Calc. : 2·4 c.c.). The benzene solution of 3 : 4-dihydro-6-methoxy-1-vinylnaphthalene was cooled rapidly to room temperature and *p*-benzoquinone (13·8 g., 1 mol.) was added, and brought into solution by swirling. The clear brown solution was set aside at room temperature in the dark. A crystalline mass commenced to separate within ½ hr. from the then warm solution. After 20 hr. methanol (80 c.c.) was added, the crystalline material was broken up, filtered, and washed with methanol, to give pale yellow needles (24·6 g.) of *cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-octahydro-8-methoxy-1 : 4-dioxochrysene, m. p. 152—156°. A further crop (2·6 g.) could be obtained by evaporation of the mother-liquors and washings to small bulk. The m. p. was raised to 161° (decomp.) by

recrystallisation from benzene–light petroleum (Found : C, 77·5; H, 6·4. Calc. for $C_{19}H_{18}O_3$: C, 77·6; H, 6·1%). Dane *et al.*[16] record m. p. 160—161° (decomp.).

Aromatisation of cis-syn-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Octahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (III).—(a) *By acid. Formation of* 5 : 6 : 11 : 12-*tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (V). *cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Octahydro-8-methoxy-1 : 4-dioxochrysene (2·0 g.), suspended in acetic acid (50 c.c.), was treated with a 50% solution of hydrogen bromide in acetic acid (5 c.c.). The solid immediately dissolved and a greenish colour was produced. After a few minutes the colour changed to blue-black, and the solution showed a strong fluorescence in ultraviolet light. After 2 hr. at room temperature, when the colour had faded to pale violet, the solution was poured into water, and the precipitated blue-grey solid was collected. Crystallisation from toluene afforded 5 : 6 : 11 : 12-*tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (V) (1·41 g.) in greyish-white leaflets, m. p. (micro) 201—204°, rapidly becoming blue-grey (Found : C, 77·1; H, 6·4. $C_{19}H_{18}O_3$ requires C, 77·6; H, 6·1%). The presence of the 15 : 16-olefinic double bond was indicated by the ultraviolet light absorption : $\lambda_{max.}$ *ca.* 207, 327, and 339 mμ (log ε 4·46, 4·30, and 4·31 respectively) (Fig. 1). The substance gave a Burgundy-red colour with ferric chloride in methanol, changing to bluish-purple on dilution with water.

(b) *By alkali. Formation of* 5 : 6 : 12 : 15-*tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (IV). A solution of *cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-octahydro-8-methoxy-1 : 4-dioxochrysene (0·5 g.) and sodium acetate (0·5 g.) in warm ethanol (100 c.c.) was treated under nitrogen with N-sodium hydroxide (5 c.c.). As soon as the solutions had mixed, N-hydrochloric acid (5·5 c.c.) was added to neutralise the alkali. The product, isolated by dilution with water and extraction with chloroform, was recrystallised from benzene, affording 5 : 6 : 12 : 15-*tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (IV) in needles, m. p. (micro) 110—115° and, after resolidification, 175—182° (decomp.), rapidly darkening (Found : C, 77·3; H, 6·1%). The presence of the olefinic 11 : 16-double bond was indicated by the ultraviolet light absorption : $\lambda_{max.}$ 261 and 294 mμ (log ε 4·02 and 3·76) (Fig. 1). The substance gave no colour with ferric chloride in methanol.

Acid Isomerisation of 5 : 6 : 12 : 15-*Tetrahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (IV).—The substance (IV) (100 mg.), dissolved in hot benzene (5 c.c.), was treated with one drop of a 50% solution of hydrogen bromide in glacial acetic acid. After 1 min. the clear solution was seeded with the $\Delta^{15:16}$-isomer and crystallisation commenced. At the end of 1 hr. filtration afforded 5 : 6 : 11 : 12-tetrahydro-1 : 4-dihydroxy-8-methoxychrysene (V) (80 mg.), m. p. (micro) 201—205°, not depressed on admixture with the specimen prepared, as above, directly from the diketone (III).

cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VI).—*cis-syn*-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Octahydro-8-methoxy-1 : 4-dioxochrysene (III) (9·0 g.), dissolved in acetic acid (450 c.c.) by gentle warming and then cooled to *ca.* 25°, was treated with zinc powder (9 g.), added in several portions with shaking and water-cooling during 3—4 min. A second portion of zinc powder (9 g.) was then added all at once and shaking was continued for a further 5 min.; cooling was not usually necessary during this second addition. The product separated during the reduction as a fine crystalline suspension. The reaction mixture was poured into water (1·5 l.) and extracted three times with chloroform, each extract being filtered as rapidly as possible from entrained zinc. The combined chloroform extracts were washed with water, with dilute aqueous sodium hydrogen carbonate solution, and again with water, and evaporated under reduced pressure until crystals began to separate. Crystallisation was completed by the addition of methanol to give cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VI) as needles (7·5 g.), m. p. 194—196° (decomp.); a further quantity (0·97 g.) was obtained from the mother-liquors on evaporation (Found : C, 77·3; H, 6·7. $C_{19}H_{20}O_3$ requires C, 77·0; H, 6·8%). The presence of the olefinic 11 : 16-double bond was indicated by the ultraviolet light absorption : $\lambda_{max.}$ 264 and 299 mμ (log ε 4·23 and 3·60) (Fig. 2).

Acid Isomerisation of cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VI). cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VII).—*cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Decahydro-8-methoxy-1 : 4-dioxochrysene (1·0 g.) was dissolved in a warm mixture of ethanol (50 c.c.) and chloroform (30 c.c.), and the solution was heated under reflux with concentrated hydrochloric acid (4 c.c.) for 30 min. A clear yellow colour rapidly developed. Distillation of part of the solvent (to remove the chloroform) gave a clear yellow solution which was cooled and diluted with water to cloudiness. The crystals (180 mg.) which separated were collected, and recrystallisation from ethanol gave a *compound*, $C_{21}H_{22}O_3$, as white needles, m. p. (micro) 119—120·5°, which lacked ketonic properties

(Found: C, 82·2; H, 7·2. $C_{21}H_{32}O_3$ requires C, 82·3; H, 7·2%). Ultraviolet light absorption in hexane: $\lambda_{max.}$ 316, 330, and 346 mμ (log ε 4·38, 4·44, and 4·29 respectively).

The reaction mixture, after separation of the compound $C_{21}H_{32}O_3$, was poured into water and extracted twice with chloroform. The combined extracts, washed with water, dried, and evaporated, gave a solid residue, which, after several crystallisations from ethanol, gave cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VII) as flattened pale yellow needles (0·3 g.), m. p. (micro) 154—157° (decomp.) (Found: C, 77·3; H, 6·9. $C_{19}H_{20}O_3$ requires C, 77·0; H, 6·8%). The presence of the olefinic 15 : 16-double bond was indicated by the ultraviolet light absorption: $\lambda_{max.}$ 273·5 mμ (log ε 4·16) (Fig. 2). Reduction of this substance (VII) (100 mg.) with lithium aluminium hydride in tetrahydrofuran gave the *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1 : 4-dihydroxy-8-methoxychrysene (XVI) described below (70 mg.), m. p. and mixed m. p. (micro) 150—152·5°.

Repetition of the acid isomerisation of *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (VI) but employing methanol as the sole solvent gave again a mixture. The main product was *cis*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (VII) as before, but the minor product was a *compound*, m. p. (micro) 125—127°, depressed on admixture with the compound $C_{21}H_{32}O_3$ (above) (m. p. 119—120·5°) (Found: C, 82·2; H, 6·9; OMe, 21·7. $C_{20}H_{30}O_2$ requires C, 82·2; H, 6·9; 2OMe, 21·2%). The ultraviolet light absorption characteristics of this substance closely resembled those of the C_{21} compound.

cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*Dodecahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (X).—cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-Decahydro-8-methoxy-1 : 4-dioxochrysene (VI) (1·0 g.), suspended in ethanol (100 c.c.), was hydrogenated at room temperature and atmospheric pressure in the presence of 2% palladised strontium carbonate (1 g.). Absorption of hydrogen ceased after 4 hr. (uptake, 0·93 mol.). Removal of the catalyst and evaporation to small bulk under reduced pressure with gentle warming gave colourless prisms (0·73 g.), m. p. (micro) 153—163°; the yellow mother-liquors gave only gum on evaporation. Recrystallisation of the solid product from ethanol–chloroform left, on each occasion, yellow decomposition products in the mother-liquor, with cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*dodecahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (X) separating in prisms, m. p. (micro) 160—165° (decomp.) (Found: C, 76·5; H, 7·7. $C_{19}H_{22}O_3$ requires C, 76·5; H, 7·4%). Ultraviolet light absorption: $\lambda_{max.}$ 280 mμ (log ε 3·44) (Fig. 2).

cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*Dodecahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XII).—*cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-Dodecahydro-8-methoxy-1 : 4-dioxochrysene (X) (0·75 g.) in ethyl acetate (100 c.c.) was hydrogenated at room temperature and atmospheric pressure in the presence of Adams platinum oxide catalyst (100 mg.). Approx. 1 mol. of hydrogen was absorbed in 28 hr. and crystals separated. After the addition of some chloroform to effect complete solution, the catalyst was removed and the solvent was evaporated under reduced pressure. Crystallisation of the solid residue from chloroform–ethanol gave cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*dodecahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XII) as prisms (0·60 g.), m. p. (micro) 205—208° (Found: C, 75·8; H, 8·1. $C_{19}H_{24}O_3$ requires C, 76·0; H, 8·1%).

trans-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*Dodecahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XV).—*cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-Dodecahydro-4-hydroxy-8-methoxy-1-oxochrysene (XII) (0·68 g.) was heated under reflux for 1 hr. in 1% ethanolic potassium hydroxide (80 c.c.), and the solution was then cooled and poured into an excess of dilute aqueous hydrochloric acid. The precipitated solid was collected, and recrystallisation from *iso*butyl alcohol afforded colourless prisms (0·54 g.) of trans-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*dodecahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene*, (XV), m. p. (micro) 221—224° (Found: C, 75·8; H, 8·1. $C_{19}H_{24}O_3$ requires C, 76·0; H, 8·1%).

cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*Dodecahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XI).—(a) *By catalytic hydrogenation of* cis-syn-1 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*octahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (III). The diketone (III) (1·0 g.) in glacial acetic acid (100 c.c.) was hydrogenated at room temperature and atmospheric pressure in the presence of Adams's platinum oxide catalyst (150 mg.), the reduction being interrupted when the uptake of hydrogen amounted to 4 mols. Removal of the catalyst and distillation under reduced pressure gave a solid residue, affording, after several recrystallisations from benzene–light petroleum or from ethyl acetate, *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-1 : 4-dihydroxy-8-methoxychrysene (XI) as needles, m. p. (micro) 155° (transition), 169—172° (Found: C, 75·5; H, 8·5. Calc. for $C_{19}H_{26}O_3$: C, 75·5; H, 8·7%). Oxidation with chromium trioxide (2·5 equiv.)

in acetic acid gave *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-8-methoxy-1 : 4-dioxochrysene (X) in poor yield (*ca.* 10%).

(b) *By reduction of* cis-syn-cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-*dodecahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (X) *with lithium aluminium hydride.* The diketone (X) (100 mg.) was heated under reflux in tetrahydrofuran (20 c.c.) with lithium aluminium hydride (400 mg.) for 1 hr. After destruction of excess of reagent with ethyl acetate, dilute sulphuric acid and chloroform were added, and the product was recovered from the organic phase in the usual way. Recrystallisation from ethyl acetate gave *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-1 : 4-dihydroxy-8-methoxychrysene (XI) (60 mg.), m. p. (micro) 158—161° and 170—173°, not depressed on admixture with a specimen prepared as in (a) (above).

Reduction of cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VI) *with Lithium Aluminium Hydride.*—(a) cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVI). The diketone (VI) (0·5 g.) in warm tetrahydrofuran (50 c.c.) was added slowly to a suspension of lithium aluminium hydride (1·0 g.) in tetrahydrofuran (25 c.c.). After being heated for 1 hr. under reflux, the mixture was cooled and excess of reagent was destroyed by the addition of ethyl acetate. The inorganic material was then dissolved by the addition of excess dilute sulphuric acid with vigorous shaking. Finally chloroform was added and the product was isolated from the organic phase in the usual way. Crystallisation of the residue from ethyl acetate–light petroleum then gave cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVI) as colourless plates (0·48 g.), m. p. (micro) 152—156° (Found : C, 76·2; H, 7·9. $C_{19}H_{24}O_3$ requires C, 76·0; H, 8·1%). The presence of the olefinic 15 : 16-double bond was indicated by the ultraviolet light absorption : $\lambda_{max.}$ 273 mμ (log ε 4·23).

The substance (XVI) (200 mg.) was hydrogenated in glacial acetic acid (20 c.c.) at room temperature and atmospheric pressure in presence of Adams's platinum oxide catalyst (50 mg.) until 1 mol. of hydrogen had been absorbed. Removal of the catalyst and evaporation under reduced pressure gave a solid residue, which afforded, after two recrystallisations from ethyl acetate, *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-1 : 4-dihydroxy-8-methoxychrysene (XI) (90 mg.), m. p. and mixed m. p. (micro) 173—176°.

(b) cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVII). The diketone (VI) (2·0 g.) in warm tetrahydrofuran (120 c.c.) was added slowly to a stirred slurry of lithium aluminium hydride (2·0 g.) in tetrahydrofuran (30 c.c.), cooled in an ice-bath. At the end of the addition the mixture was heated to boiling and then again cooled in ice. Water was cautiously added to decompose excess of reagent and then in sufficient amount to give a thick paste with the precipitated inorganic material, from which the organic layer was decanted. The solid residue left on evaporation was crystallised from ethanol–ethyl acetate, affording cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVII) (1·66 g.) as leaflets, m. p. (micro) 183—185° (Found : C, 76·3; H, 8·2%). Retention of the ethylenic 11 : 16-double bond was indicated by the ultraviolet light absorption : $\lambda_{max.}$ 265 and 300 mμ (log ε 4·28 and 3·54).

A sample, heated under reflux for ½ hr. in a mixture of ethanol and concentrated hydrochloric acid (25 : 1), was completely transformed into the *cis*-isomer (XVI), m. p. (micro) 152—156°, described in (a) (above).

Oppenauer Oxidation of cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVI). trans-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XIII).—The diol (XVI) (1·0 g.) was heated under reflux in benzene (50 c.c.) and *cyclo*hexanone (10 c.c.) with aluminium *iso*propoxide (1 g.) for 48 hr. After cooling, water (2 c.c.) was added, and the mixture was shaken and filtered. The filtrate was evaporated under reduced pressure, finally at 100°/0·1 mm., and the viscous residue was dissolved in a little methanol. The crystals which separated were twice recrystallised from ethyl acetate–light petroleum to give trans-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XIII) as prisms (0·40 g.), m. p. (micro) 177—179° (Found : C, 76·5; H, 7·7. $C_{19}H_{22}O_3$ requires C, 76·5; H, 7·6%). Ultraviolet light absorption : $\lambda_{max.}$ 275 mμ (log ε 4·21).

The hydroxy-ketone (XIII) (100 mg.) in tetrahydrofuran (15 c.c.) was added to a slurry of lithium aluminium hydride (400 mg.) in tetrahydrofuran (5 c.c.) and the mixture was heated under reflux for 30 min. After cooling and decomposition of excess of reagent by water, chloroform and dilute sulphuric acid were added and the solid product was recovered from the organic phase in the usual way. Several recrystallisations from ethyl acetate then gave trans-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVIII), prisms, m. p. (micro) 220—224° (Found : C, 75·8; H, 7·9. $C_{19}H_{24}O_3$ requires C, 76·0; H, 8·1%).

Conversion of trans-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XIII) *into* 8-*Methoxy*-1-*methylchrysene* (XIV).—The hydroxy-ketone (XIII) (0·5 g.) was added in warm benzene (50 c.c.) to methylmagnesium iodide (from 2·0 g. of magnesium) in boiling benzene (100 c.c.) and the mixture was refluxed for 29 hr. (total). After cooling in ice and decomposition of excess of reagent with ice-cold 3N-sulphuric acid, the organic layer was separated, and the aqueous phase was extracted once with benzene. The combined organic layers were washed with water and evaporated to give a solid non-ketonic residue, which was heated with powdered anhydrous potassium hydrogen sulphate (3·0 g.) in nitrogen at 180—200° for 30 min. After cooling, the cake was leached with water, and organic material was taken up in benzene. The benzene extract, washed and evaporated, gave a green oil, which was mixed with diphenylamine (10 g.) and palladised charcoal (1·0 g. of 10%) and dehydrogenated under reflux for 5 hr. After cooling, the reaction mixture was extracted with ether. The ethereal solution was filtered, saturated with dry hydrogen chloride, again filtered to remove the precipitated diphenylamine hydrochloride, and evaporated. Recrystallisation of the residue from benzene then afforded 8-methoxy-1-methylchrysene (XIV), leaflets (70 mg.), m. p. (micro) 263—265° (after a transition to liquid crystals above 190°), not depressed on admixture with an authentic specimen prepared as described in the following paper and showing identical ultraviolet light absorption behaviour.

Oppenauer Oxidation of cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-1 : 4-*dihydroxy*-8-*methoxychrysene* (XVII). cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XIX).—The diol (XVII) (1·0 g.) was oxidised as described in the case of the isomeric $\Delta^{15:16}$-diol (XVI) (above). The solid which separated after treatment with methanol was twice crystallised from ethyl acetate–light petroleum, to give cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XIX), leaflets (0·26 g.), m. p. (micro) 191—194° (Found: C, 76·6; H, 7·6. $C_{19}H_{22}O_3$ requires C, 76·5; H, 7·6%). Retention of the ethylenic 11 : 16-double bond was indicated by the ultraviolet light absorption: $\lambda_{max.}$ 265 and 300 mμ (log ε 4·57 and 3·84).

The hydroxy-ketone (XIX) (100 mg.) was added in tetrahydrofuran (20 c.c.) at room temperature to lithium aluminium hydride (200 mg.) in tetrahydrofuran (10 c.c.). After 30 min. with occasional shaking the mixture was cooled in ice, decomposed with a solution of sodium potassium tartrate, poured into water, and extracted twice with chloroform. The product, recovered from the combined washed extracts, was crystallised from ethyl acetate, affording *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-1 : 4-dihydroxy-8-methoxychrysene (XVII), m. p. and mixed m. p. (micro) 179—184°.

The hydroxy-ketone (XIX) (50 mg.) was heated under reflux in ethanol (5 c.c.) with one drop of concentrated hydrochloric acid for 10 min. After cooling, water was added to cloudiness; *trans*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XIII) separated, having m. p. and mixed m. p. (micro) 177—179°.

The hydroxy-ketone (XIX) suffers partial decomposition to brown material when kept at room temperature in benzene–ethanol solution in the presence of sodium ethoxide, but some (XIX) was recoverable unchanged. Similarly from a boiling solution in 5% ethanolic potassium hydroxide (1 hr.) it (XIX) was largely recovered unchanged.

Catalytic hydrogenation of the hydroxy-ketone (XIX) (200 mg.) in ethanol (70 c.c.) in the presence of 2% palladised strontium carbonate (200 mg.) was rapid and ceased after the uptake of approx. 1 mol. Removal of the catalyst and evaporation gave a mixture of leaflets (A) and prisms (B), which were separated as far as possible by hand-sorting. Recrystallisation of fraction (B) from ethyl acetate afforded prisms, m. p. (micro) 175—191°, not improved by recrystallisation; the ultraviolet light absorption ($\lambda_{max.}$ 275 mμ; log ε 4·16) indicated the presence of a 15 : 16-double bond, and a mixed m. p. with *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XX) (see following paper), m. p. (micro) 192—193°, showed no further extension of the m. p. range. The essential identity of fraction (B) with (XX) was confirmed by their infrared absorption spectra. Fraction (A) on recrystallisation from ethanol–ethyl acetate gave *cis-syn-cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14 : 15 : 16-dodecahydro-4-hydroxy-8-methoxy-1-oxochrysene (XII) (90 mg.), m. p. and mixed m. p. (micro) 200—208°.

Catalytic Hydrogenation of cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (VII). cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-1-*hydroxy*-8-*methoxy*-4-*oxochrysene* (XXI).—The diketone (VII) (300 mg.) was hydrogenated in ethyl acetate (30 c.c.) at room temperature and atmospheric pressure in the presence of Adams's platinum oxide catalyst (100 mg.). 1 Mol. of hydrogen was rapidly absorbed and uptake then ceased. The solid residue obtained on removal of the catalyst and evaporation of the solution was

crystallised from ethyl acetate, affording cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-1-*hydroxy*-8-*methoxy*-4-*oxochrysene* (XXI), needles (160 mg.), m. p. (micro) 167—168° (Found : C, 76·6; H, 7·5. $C_{19}H_{22}O_3$ requires C, 76·5; H, 7·4%). Ultraviolet light absorption : $\lambda_{max.}$ 272 mμ (log ε 4·20). Reduction of a sample with lithium aluminium hydride gave *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1 : 4-dihydroxy-8-methoxychrysene (XVI), m. p. and mixed m. p. (micro) 152—156°.

The hydroxy-ketone (XXI) was decomposed by heating it under reflux for 1 hr. with 5% ethanolic potassium hydroxide. It was in part recovered unchanged after being adsorbed on to a column of alkaline alumina overnight and then eluted, the only other material recovered consisting of dark decomposition products.

An attempt was made to effect equilibration with perchloric acid in ethyl acetate. The hydroxy-ketone (XXI) (150 mg.) in alcohol-free ethyl acetate (13 c.c.) was treated with perchloric acid (0·2 c.c. of 72%), and the mixture was kept overnight at room temperature. After dilution with benzene and washing with aqueous sodium hydrogen carbonate the product was recovered, and crystallisation from methanol afforded the *acetate* of (XXI) as needles (70 mg.), m. p. 164—168° (Found : C, 74·4; H, 7·2. $C_{21}H_{24}O_4$ requires C, 74·2; H, 7·1%). Light absorption : (i) infrared, 1250 cm.$^{-1}$ (s) and 1730 cm.$^{-1}$ (s) (acetate); (ii) ultraviolet, $\lambda_{max.}$ 272 mμ (log ε 4·20). The substance was identical in m. p., and there was no depression of the m. p. on admixture, with the acetate prepared directly from (XXI) with acetic anhydride–pyridine at room temperature.

National Institute for Medical Research,
The Ridgeway, Mill Hill, London, N.W.7.

[*Received, April 20th*, 1956.]

---

633. *A New and Specific Aromatisation Reaction. Part I. Direct Conversion of* cis-syn-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene into* 1-*Alkoxy*-5 : 6 : 11 : 12-*tetrahydro*-8-*methoxychrysenes.*

By P. A. Robins and James Walker.

It is shown that by-products formed during the isomerisation of *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (I) into *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-8-methoxy-1 : 4-dioxochrysene (II) in hot alcohol in the presence of aqueous hydrochloric acid are 1-alkoxy-5 : 6 : 11 : 12-tetrahydro-8-methoxychrysenes (XIII). The compositions of these substances correspond to the addition to (II) of the elements of the alcohol employed and the loss of two molecules of water, and a mechanism is proposed for this novel aromatisation of a 1 : 4-dioxohexamethylene ring to give an alkoxylated benzene ring.

Precise conditions for the preparation of the 1-alkoxy-5 : 6 : 11 : 12-tetrahydro-8-methoxychrysenes (XIII) as major products have been established, and ready ketal formation by the carbonyl group in the 1-position of the *cis*-diketone (II) has been demonstrated.

In the preceding communication it was noted that in the conversion of *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (I) into *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-8-methoxy-1 : 4-dioxochrysene (II) in hot ethanolic hydrochloric acid there was formed in about 20% yield a by-product $C_{21}H_{22}O_2$, and in methanolic hydrochloric acid a similar by-product $C_{20}H_{20}O_2$, containing two methoxyl groups. The ultraviolet light absorptions of these two substances were virtually indistinguishable and markedly different from those of their precursors, indicating a radical change in structure. The two methoxyl groups in the latter compound, $C_{20}H_{20}O_2$, accounted for the two oxygen atoms, and the original two carbonyl groups had disappeared. The substances were, in fact, apparently derived from the diketone (I) or (II) by the loss of the elements of two molecules of water and the addition of the elements of the alcohol employed, and it is the object of the present communication to demonstrate the structures of these compounds and to propose a mechanism for their formation.

The ultraviolet light absorption spectra of the compounds $C_{20}H_{20}O_2$ and $C_{21}H_{22}O_2$ (Fig. 1) showed intense absorption in the 310—350 mμ region with maxima at 316, 330, and 346 mμ, strongly reminiscent of the spectrum of *trans*-stilbene in which the three maxima

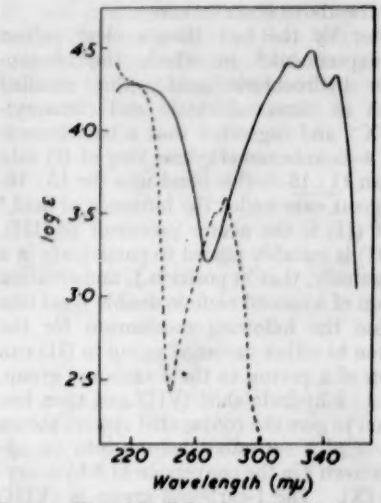


FIG. 1. *Ultraviolet light absorption, in hexane, of* 5 : 6 : 11 : 12-*tetrahydro*-1 : 8-*dimethoxychrysene* (III; R = Me) (——), *and* cis-5 : 6 : 11 : 12 : 15 : 16-*hexahydro*-1 : 8-*dimethoxychrysene* (IV; R = Me) (– – – –).

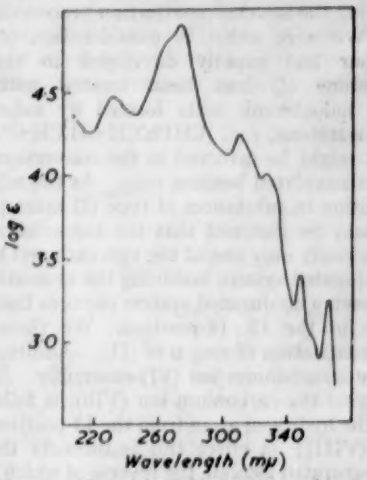
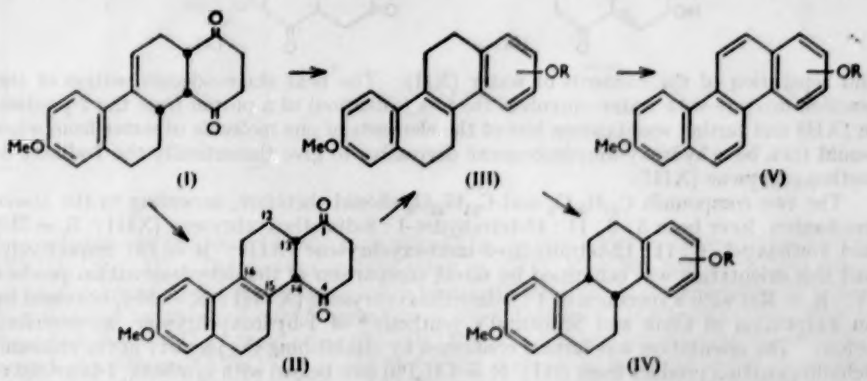


FIG. 2. *Ultraviolet light absorption of* 1 : 8-*dimethoxychrysene* (V; R = Me) *in hexane.*

are each shifted by about 20 mμ to shorter wavelengths,[1] so that structure (III) may therefore be provisionally assigned to the substances $C_{20}H_{20}O_2$ and $C_{21}H_{22}O_2$. In agreement with this view, catalytic hydrogenation of the two compounds in acetic acid in presence of Adams's platinum oxide catalyst stopped after the absorption of one mol. of hydrogen,

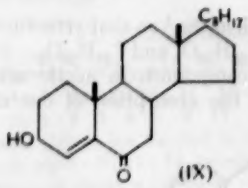


to give two new compounds (IV), having ultraviolet light absorption spectra (Fig. 1) of the anisole type,[2] and indicating that hydrogenation had saturated the olefinic double bond in (III) to give, in each case, a substance (IV) containing two isolated benzenoid chromophores.

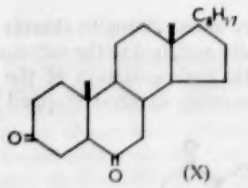
[1] Cf. Beale and Roe, *J.*, 1953, 2757.
[2] Cf. Wolf and Herold, *Z. phys. Chem.*, 1931, **13**, *B*, 225.

Furthermore, dehydrogenation of the substance $C_{20}H_{20}O_2$ with chloranil in boiling anisole afforded a substance $C_{20}H_{16}O_2$, containing two methoxyl groups and having an ultraviolet light absorption spectrum (Fig. 2) typical [3] of a fully aromatic chrysene derivative (V). It therefore remained to establish the point of attachment of the alkoxy-group introduced during the novel aromatisation process disclosed by the above observations.

We were aided in consideration of this matter by the fact that a clear yellow colour had rapidly developed in the initial experiment [4] in which the *cis-syn*-diketone (I) had been treated with ethanolic hydrochloric acid; this recalled the halochromic salts formed by substances such as cinnamaldehyde and cinnamylideneacetone, *e.g.*, $[CHPh{:}CH{\cdot}CH{:}CH{\cdot}C^{+}(OH){\cdot}CH_3]X^{-}$, and suggested that a halochromic salt might be involved in the conversion of the 1 : 4-dioxohexamethylene ring of (I) into an alkoxylated benzene ring. As the migration of an 11 : 16-double bond into the 15 : 16-position in substances of type (I) takes place with great ease under the influence of acid,[4] it may be assumed that the isomerisation product (II) is the nearer precursor of (III). Obviously only one of the two carbonyl groups in (II) is suitably placed to participate in a conjugated system involving the aromatic nucleus, namely, that in position 1, and creation of such a conjugated system requires the introduction of a second olefinic double bond into (II) in the 13 : 14-position. We therefore propose the following mechanism for the aromatisation of ring D of (II). Addition of a proton to either carbonyl group in (II) can give a carbonium ion (VI) reversibly. The addition of a proton to the 4-carbonyl group, to give the carbonium ion (VIb), is followed by a 1 : 2-hydride shift (VII) and then loss of the hydrogen atom from the 13-position as a proton to give the conjugated system shown in (VIII); in effect this is formally the conversion of a saturated ketone into an $\alpha\beta$-unsaturated alcohol, the reverse of which is already known [5] in the conversion of 3-hydroxycholest-4-en-6-one (IX) into cholestane-3 : 6-dione (X). The 1-carbonyl group in (VIII) is now favourably placed for the formation of a halochromic salt (XI), and metathetic replacement of the 1-hydroxyl group by alkoxyl could take place by presentation of a pair of unshared electrons by the oxygen atom of the alcohol to the carbonium carbon atom



(IX)



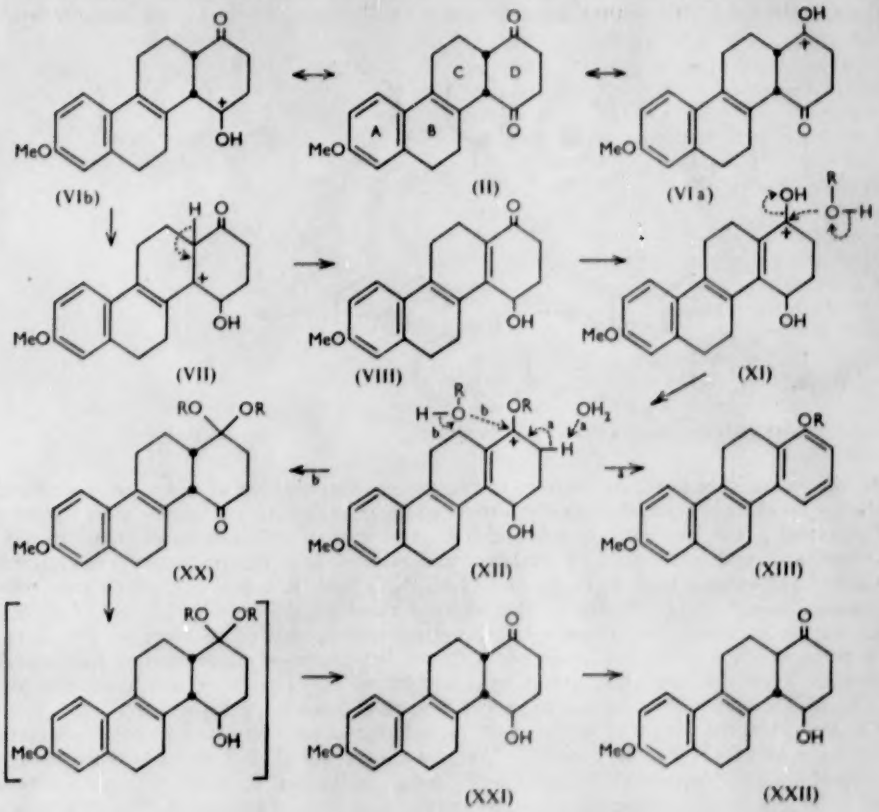
(X)

and separation of the elements of water (XII). The next stage—decomposition of the reaction mixture with water—involves the loss (solvation) of a proton from the 2-position in (XII) and further spontaneous loss of the elements of one molecule of water from what would then be a hydroxy-dihydrobenzene derivative to give theoretically the 1-alkoxy-8-methoxychrysene (XIII).

The two compounds $C_{20}H_{20}O_2$ and $C_{21}H_{22}O_2$ should therefore, according to the above mechanism, have been 5 : 6 : 11 : 12-tetrahydro-1 : 8-dimethoxychrysene (XIII; R = Me) and 1-ethoxy-5 : 6 : 11 : 12-tetrahydro-8-methoxychrysene (XIII; R = Et) respectively, and this orientation was confirmed by direct comparison of the dehydrogenation product (V; R = Me) with a specimen of 1 : 8-dimethoxychrysene (XVIII; R = Me), obtained by an adaptation of Cook and Schoental's synthesis [6] of 1-hydroxychrysene, as described below. The orientation was further confirmed by establishing the identity of the chloranil dehydrogenation product from (III; R = CH_2Ph) (see below) with synthetic 1-benzyloxy-8-methoxychrysene (XVIII; R = CH_2Ph).

[3] Cf. Holiday and Jope, *Spectrochim. Acta*, 1950, **4**, 157.
[4] Robins and Walker, preceding paper.
[5] Heilbron, Jones, and Spring, *J.*, 1937, 801; cf. Butenandt and Schramm, *Ber.*, 1936, **69**, 2289; Butenandt and Hausmann, *Ber.*, 1937, **70**, 1154; Jeanloz, Prins, and von Euw, *Helv. Chim. Acta*, 1947, **30**, 374; Herzig and Ehrenstein, *J. Org. Chem.*, 1951, **16**, 1050.
[6] Cook and Schoental, *J.*, 1945, 288.

The Reformatsky reaction with zinc and methyl γ-bromocrotonate was applied to 1 : 2 : 3 : 4-tetrahydro-7-methoxy-1-oxophenanthrene (XIV), prepared by a combination of the methods of Stork [7] and of Ross,[8] and the methyl ester (XV; R = Me) of the resulting γ-(1 : 2 : 3 : 4-tetrahydro-7-methoxy-1-phenanthrylidene)crotonic acid (XV; R = H) was rearranged when heated with palladium black to methyl γ-(7-methoxy-1-phenanthryl)butyrate (XVI; R = Me). The free acid (XVI; R = H) was cyclised with anhydrous hydrofluoric acid to give 1 : 2 : 3 : 4-tetrahydro-7-methoxy-1-oxochrysene (XVII), and dehydrogenation of this with palladium black in boiling α-methylnaphthalene

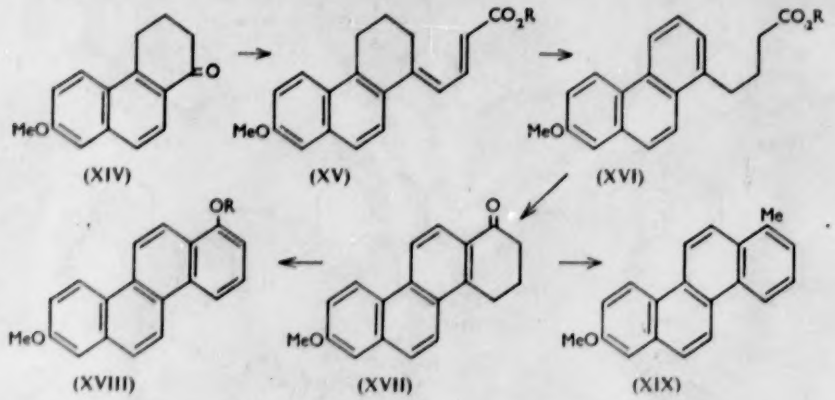


proceeded slowly and incompletely, even after 72 hr., to give 1-hydroxy-8-methoxychrysene (XVIII; R = H). The derived methyl ether (XVIII; R = Me) had m. p. and ultraviolet and infrared light absorption spectra identical with those of the substance (V; R = Me) obtained by chloranil dehydrogenation of the substance $C_{20}H_{20}O_2$ (III; R = Me), as described above. The benzyl ether (XVIII; R = CH_2Ph) was obtained by the action of benzyl chloride on (XVIII; R = H) in boiling acetone in the presence of potassium carbonate. Treatment of the ketone (XVII) with methylmagnesium iodide, followed by dehydration of the resulting alcohol and dehydrogenation, afforded 8-methoxy-1-methylchrysene (XIX) required as a reference substance in the preceding communication.[4]

Having shown that the above mechanism predicted the orientation of the products

[7] Stork, *J. Amer. Chem. Soc.*, 1947, **69**, 2936.
[8] Ross, *J.*, 1947, 1365.

obtained by the aromatisation of ring D in (I), or (II), in the presence of hydrochloric acid and an alcohol, we then turned to the possibility of establishing conditions whereby the aromatisation products (XIII) might be the major products, and the following general process, which at no stage exceeds room temperature, was found to give excellent results. The 1 : 4-dioxochrysene (I) was dissolved in alcohol-free chloroform, and the solution was saturated with dry hydrogen chloride at 0°; a cherry-red colour and a strong fluorescence developed, owing presumably to formation of the halochromic salt (XI), and subsequent addition of the alcohol did not cause a significant colour change. The mixture, containing the appropriate alcohol, was set aside overnight at room temperature, protected from moisture, some deepening and browning of the colour, but otherwise



(XIV) (XV) (XVI) (XVII) (XVIII) (XIX)

no significant change in appearance, taking place. On addition of water an immediate change in colour to greenish-brown occurred and the chloroform layer became more strongly fluorescent. The products, recovered from the washed chloroform solutions, readily crystallised, and in the case of methanol and ethanol were the previously encountered methyl and ethyl ethers, $C_{20}H_{20}O_2$ and $C_{21}H_{22}O_2$ (XIII; R = Me, Et), which were now obtained in high yield. Benzyl alcohol afforded a new benzyl ether (XIII; R = CH_2Ph), having an ultraviolet light absorption spectrum closely related to those of the corresponding methyl and ethyl analogues with the superimposed absorption of the benzyl group. That the benzyloxy-group was in fact in the 1-position was confirmed by dehydrogenation with chloranil to give 1-benzyloxy-8-methoxychrysene (XVIII; R = CH_2Ph), identical with that prepared by benzylation of authentic 1-hydroxy-8-methoxychrysene (XVIII; R = H) (above). When, however, no alcohol was added to the red chloroformic hydrogen chloride solution of the *cis-syn*-diketone (I) before the final addition of water, the usual working-up procedure gave as sole product the *cis*-diketone (II), which could, of course, itself be utilised as the starting material for the aromatisation, when alcohol was added to its red solution in chloroformic hydrogen chloride. The *cis*-diketone (II) was also the product when acetic acid was added instead of an alcohol to the chloroformic hydrogen chloride solution of (I) before the addition of water. The formation of the *cis*-1 : 4-diketone by reaction of the halochromic salt with water implies, according to our proposed mechanism, reversion of (IX) to (VIII) and reversion of (VIII) to (II), on the analogy of the conversion of (XI) into (X). The formation of the *cis*-diketone (II) is, moreover, in accord with considerations which we have previously advanced [9] concerning the stereochemical stability of fused 1 : 4-dioxo*cyclo*hexane rings.

A further interesting property of the 1-carbonyl group in the *cis*-diketone (II) was the very great ease with which it formed a dimethyl ketal. A few minutes at the boiling point in methanol containing a trace of hydrogen chloride sufficed to convert it in excellent yield

[9] Robins and Walker, *J.*, 1955, 1789; *Chem. and Ind.*, 1955, 772.

into *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1 : 1 : 8-trimethoxy-4-oxochrysene (XX; R = Me), and an extension [(XII) $\xrightarrow{b}$ (XX)] of the preceding mechanism may be advanced to explain this ready ketal-formation at $C_{(1)}$. Proof that the 1-carbonyl group was involved in the ketal-formation was obtained in the following way. Reduction with lithium aluminium hydride and decomposition of the reaction mixture with cold dilute sulphuric acid afforded *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XXI), identical with the substance obtained on migration of the double bond in *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (preceding communication) into the 15 : 16-position. The keto-alcohol (XXI) was converted by alcoholic alkali into *trans*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XXII), in which the position of the carbonyl group was established (preceding communication) by its conversion *via* the Grignard reaction into 8-methoxy-1-methylchrysene (XIX).

The similarity between the ultraviolet light absorption of the 1-alkoxy-5 : 6 : 11 : 12-tetrahydro-8-methoxychrysenes (XIII) and that of *trans*-stilbene noted above is of some interest, the bathochromic shifts observed in the case of (XIII) being attributable to the alkoxyl groups. The introduction of an α-methyl substituent into *trans*-stilbene produces a hypsochromic shift of *ca.* 25 mμ, and the introduction of a second alkyl group, in the αβ-dialkylstilbenes, produces a further hypsochromic shift of *ca.* 30 mμ, due to steric interference between the alkyl groups and the respective β-situated aryl groups, the intensity of absorption being also diminished.[10] The effect of introducing the two ethano-bridges in (XIII) is therefore to restore the approximate coplanarity of the molecule with restoration of the ultraviolet light absorption spectrum of *trans*-stilbene. Precisely similar effects are seen in passing from diphenyl to 2 : 2′-substituted diphenyls and thence to 2 : 2′-bridged diphenyls (*e.g.*, 9 : 10-dihydrophenanthrene).[11]

Experimental

General details concerning the observation of m. p.s and the measurement of ultraviolet light absorption are given in the preceding paper.

Catalytic Hydrogenation of 1-*Alkoxy*-5 : 6 : 11 : 12-*tetrahydro*-8-*methoxychrysenes* (XIII; R = Me, Et).—The tetrahydrochrysene (XIII; R = Me) (200 mg.) was hydrogenated in glacial acetic acid (20 c.c.) at room temperature and atmospheric pressure in presence of Adams's platinum oxide catalyst (50 mg.). Removal of the catalyst and distillation under reduced pressure gave a solid residue, which, after several crystallisations from benzene–methanol, afforded cis-5 : 6 : 11 : 12 : 15 : 16-*hexahydro*-1 : 8-*dimethoxychrysene* (IV; R = Me) as needles, m. p. (micro) 127—128°, depressed to 90° on admixture with the starting material (XIII; R = Me) (m. p. 125—127°) (Found : C, 81·4; H, 7·5; OMe, 20·9. $C_{20}H_{22}O_2$ requires C, 81·6; H, 7·5; OMe, 20·7%). Ultraviolet light absorption in hexane : $\lambda_{max.}$ 220 (infl.), 273 (infl.), and 279 mμ (log ε 4·3, 3·50, and 3·60 respectively) (Fig. 1).

Similarly, catalytic hydrogenation of the homologue (XIII; R = Et) gave cis-1-*ethoxy*-5 : 6 : 11 : 12 : 15 : 16-*hexahydro*-8-*methoxychrysene* (IV; R = Et), which crystallised from ethanol in colourless plates, m. p. (micro) 96—98° (Found : C, 81·8; H, 7·8. $C_{21}H_{24}O_2$ requires C, 81·8; H, 7·8%). The ultraviolet light absorption was almost identical with that of the dimethoxy-analogue (above).

Dehydrogenation of 5 : 6 : 11 : 12-*Tetrahydro*-1 : 8-*dimethoxychrysene* (XIII; R = Me). 1 : 8-*Dimethoxychrysene* (XVIII; R = Me).—The tetrahydrochrysene (XIII; R = Me) (200 mg.) was heated in anisole (25 c.c.) under reflux with chloranil (510 mg., 3 equiv.) for 6 hr. After cooling and dilution with benzene, the solution was washed twice with aqueous alkaline sodium dithionite, then with water, and evaporated under reduced pressure. The solid residue was recrystallised from benzene–methanol to give 1 : 8-dimethoxychrysene (XVIII; R = Me) (130 mg.) as plates, m. p. (micro) 190—200° (transition to liquid crystals) and 203—205°, identical in behaviour with, and on admixture with, the synthetic material described

[10] Wessely, Bauer, Chwala, Plaichinger, and Schönbeck, *Monatsh.*, 1948, **74**, 596; Braude, *J.*, 1949, 1902.

[11] Cf. Beaven, Hall, Lesslie, and Turner, *J.*, 1952, 854.

below (Found : C, 83·5; H, 5·6; OMe, 20·8. Calc. for $C_{20}H_{16}O_3$: C, 83·3; H, 5·6; OMe, 20·5%). Ultraviolet light absorption in hexane : $\lambda_{max.}$ 231, 265 (infl.), 274, 310, 327, 348, and 366 mμ (log ε 4·47, 4·81, 4·91, 4·24, 4·01, 3·40, and 3·24 respectively) (Fig. 2). Johnson *et al.*[13] record m. p. 198—200·5°.

γ-(1 : 2 : 3 : 4-*Tetrahydro-7-methoxy-1-phenanthrylidene*)*crotonic Acid* (XV; R = H).—Zinc needles (4·5 g.) were heated in benzene (20 c.c.) under reflux with a little dry mercuric chloride for 15 min. After slight cooling, 1 : 2 : 3 : 4-tetrahydro-7-methoxy-1-oxophenanthrene[7,8] (XIV) (5·0 g.) and methyl γ-bromocrotonate (6·5 g.) were added, and stirring was started. A vigorous reaction ensued and continued for 5 min., after which the mixture was heated under reflux for 30 min. After slight cooling, zinc (2·0 g.) and methyl γ-bromocrotonate (3·0 g.) were added in benzene (10 c.c.), and heating was continued for 30 min. This addition was repeated twice more at 30 min. intervals, and the whole mixture was heated for a final 30 min., cooled in ice, and decomposed with ice and dilute sulphuric acid. The product was recovered in ether, and the extract was thoroughly washed and dried, and volatile material was removed by distillation on the steam-bath under reduced pressure. The viscous residue (10·4 g.) could with difficulty be induced to crystallise, to give the required methyl ester (XV; R = Me), but it was best hydrolysed directly, and it was therefore heated under reflux in benzene (50 c.c.) and methanol (100 c.c.) with potassium hydroxide (10 g.) for 1 hr. After cooling, the cream-coloured precipitated potassium salt was collected, washed with benzene, and dried (1·92 g.; A). Filtrate and washings were poured into water, and the whole was again filtered to yield a second crop of precipitated potassium salt (1·86 g.; B). The benzene layer of the filtrate was rejected and the aqueous phase was aerated to remove dissolved solvent, and acidified with hydrochloric acid, yielding a resinous brown precipitate (2·53 g.; C), which was collected and dried.

Precipitates A and B were dissolved in hot glacial acetic acid, and, on cooling, γ-(1 : 2 : 3 : 4-*tetrahydro-7-methoxy-1-phenanthrylidene*)*crotonic acid* (XV; R = H) separated as yellow leaflets, m. p. 235—239° (decomp.) (Found : C, 77·2; H, 6·2. $C_{19}H_{18}O_3$ requires C, 77·5; H, 6·2%). Ultraviolet light absorption : $\lambda_{max.}$ 298 and 353 mμ (log ε 4·20 and 4·54). A further quantity (0·77 g.) of less pure acid was obtained by crystallisation of the precipitate C from acetic acid.

Esterification of the acid, suspended in methanol–ether, with a slight excess of ethereal diazomethane gave the *methyl ester* (XV; R = Me), which crystallised from ligroin in yellow plates, m. p. 131—133° (Found : C, 78·0; H, 6·6. $C_{20}H_{20}O_3$ requires C, 77·9; H, 6·5%).

γ-(7-*Methoxy-1-phenanthryl*)*butyric Acid* (XVI; R = H).—The foregoing methyl ester (XV; R = Me) (200 mg.) was heated with palladium black (20 mg.) to 250—270° for 3 hr. in carbon dioxide. On cooling, the product solidified, and solution in hot ligroin and filtration afforded the *butyrate* (XVI; R = Me) as needles, m. p. 119° (Found : C, 78·1; H, 6·7. $C_{20}H_{20}O_3$ requires C, 77·9; H, 6·5%).

On a larger scale [2·15 g. of (XV; R = Me)], the rearranged methyl ester (XVI; R = Me) was hydrolysed directly after being heated with palladium (200 mg.). It was dissolved in hot benzene (50 c.c.) and poured into 10% methanolic potassium hydroxide (100 c.c.), and the whole was heated under reflux for 1·5 hr., cooled, and poured into much water. The aqueous phase, after a further extraction with benzene, was freed from traces of benzene by aeration, filtered to remove suspended palladium black, and acidified. The precipitated acid (1·8 g.) crystallised from hot glacial acetic acid, to give γ-(7-*methoxy-1-phenanthryl*)*butyric acid* (XVI; R = H) as colourless leaflets, m. p. 176—177° (Found : C, 77·3; H, 6·1. $C_{19}H_{18}O_3$ requires C, 77·5; H, 6·2%).

1 : 2 : 3 : 4-*Tetrahydro-8-methoxy-1-oxochrysene* (XVII).—The preceding acid (2·38 g.) was added to anhydrous hydrogen fluoride (20 c.c.) contained in an ice-cooled Polythene bottle. After 2 hr. in ice the hydrogen fluoride was evaporated and aqueous sodium carbonate was added to the solid residue, followed by chloroform to dissolve the insoluble part. The chloroform layer was separated, washed with water, and evaporated, to give a solid residue, affording, on crystallisation from benzene–light petroleum, 1 : 2 : 3 : 4-*tetrahydro-8-methoxy-1-oxochrysene* as leaflets (1·95 g.), m. p. 225—229° (Found : C, 82·5; H, 6·0. $C_{19}H_{16}O_3$ requires C, 82·6; H, 5·8%). Ultraviolet light absorption : $\lambda_{max.}$ 253 (infl.), 271, 280, 295 (infl.), 322 (log ε 4·17, 4·75, 4·87, 4·37, 4·27).

1-*Hydroxy-8-methoxychrysene* (XVIII; R = H).—1 : 2 : 3 : 4-Tetrahydro-8-methoxy-1-oxochrysene (0·5 g.) was heated with palladium black (90 mg.) in boiling α-methylnaphthalene (20 c.c.) in dry oxygen-free nitrogen for 24 hr. After filtration of the hot solution, cooling afforded

[13] Johnson, Banerjee, Schneider, Gutsche, Shelberg, and Chinn, *J. Amer. Chem. Soc.*, 1952, **74**, 2832.

leaflets (0·33 g.) of 1-*hydroxy*-8-*methoxychrysene* which, crystallised from butan-1-ol or ethyl methyl ketone, had m. p. 244—246° (sealed evacuated capillary), and rapidly became brown on exposure to light and air; both recrystallised samples and specimens sublimed at 210°/0·005 mm. gave low carbon figures on combustion (Found: OMe, 11·5. $C_{19}H_{14}O_2$ requires OMe, 11·3%). Ultraviolet light absorption: $\lambda_{max.}$ 225, 275, and 312 mμ (log ε 4·34, 4·78, and 4·20).

Johnson *et al.*[12] record m. p. 267·8—271° but no analysis for what was "probably" 1-hydroxy-8-methoxychrysene (XVIII; R = H). We have also prepared it, m. p. 254—258° (decomp.), by hydrogenolysis of 1-benzyloxy-8-methoxychrysene(XVIII; R = CH_2Ph), but the same difficulty was encountered in obtaining satisfactory analyses; there were also differences observed in the infrared absorption spectra of the specimens obtained as above and from (XVIII; R = CH_2Ph).

Prolonged reaction with sodium methoxide and excess of methyl iodide in boiling methanol was required to effect methylation of this substance to give 1 : 8-dimethoxychrysene (XVIII; R = Me), crystallising from benzene–methanol in leaflets, m. p. (micro) *ca.* 190° (transition to liquid crystals) and 200—205°, identical with the substance obtained by dehydrogenation of 5 : 6 : 11 : 12-tetrahydro-1 : 8-dimethoxychrysene (XIII; R = Me); ultraviolet and infrared absorption spectra confirmed the identity.

1-*Benzyloxy*-8-*methoxychrysene* (XVIII; R = CH_2Ph) was obtained from 1-hydroxy-8-methoxychrysene (100 mg.), which was heated under reflux in dry acetone (25 c.c.) with anhydrous potassium carbonate (4 g.) and benzyl chloride (1 c.c.) for 18 hr., two further portions of benzyl chloride (1 c.c.) being added at intervals. After addition of water and benzene, the product was isolated from the organic phase by evaporation of the benzene and excess of benzyl chloride under reduced pressure and sublimation of the residue at 200—220°/0·4 mm. The sublimate crystallised from benzene–methanol to give (XVIII; R = CH_2Ph) as leaflets, m. p. (micro) 158—161° (Found: C, 85·6; H, 5·4. $C_{25}H_{20}O_2$ requires C, 85·7; H, 5·6%).

8-*Methoxy*-1-*methylchrysene* (XIX).—A warm benzene solution of 1 : 2 : 3 : 4-tetrahydro-8-methoxy-1-oxochrysene (XVII) (0·5 g.) was added to methylmagnesium iodide (from 1 g. of magnesium) in boiling benzene. After 1 hour's heating under reflux the mixture was cooled in ice and decomposed with cold 3N-sulphuric acid. The organic layer was separated and washed and the product was recovered in the usual way as a solid (0·42 g.), which from its behaviour on recrystallisation, extended m. p., and analytical figures had probably undergone partial dehydration. The crude material (200 mg.) was heated under reflux in α-methylnaphthalene (20 c.c.) with palladium black (100 mg.) in dry, oxygen-free nitrogen for 20 hr. After cooling and removal of the palladium black, the solvent was distilled under reduced pressure and the residue crystallised from benzene, to give 8-*methoxy*-1-*methylchrysene* as leaflets (150 mg.), m. p. (micro) from 190° (transition to liquid crystals) and 262—263° (Found: C, 88·6; H, 6·3. $C_{20}H_{16}O$ requires C, 88·2; H, 5·9%). Ultraviolet light absorption in hexane: $\lambda_{max.}$ *ca.* 227, 266, 274, 297, 309, and 323 mμ (log ε 4·46, 4·84, 5·08, 4·22, 4·15, and 4·06).

Improved Preparations of 1-*Alkoxy*-5 : 6 : 11 : 12-*tetrahydro*-8-*methoxychrysenes* (XIII) *and of* cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-8-*methoxy*-1 : 4-*dioxochrysene* (II).—(*a*) A solution of *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (I) (0·5 g.) in alcohol-free chloroform (20 c.c.) was cooled in ice and saturated with dry hydrogen chloride. The resultant cherry-red solution was allowed to warm to room temperature and methanol (1 c.c.) was added. After being left at room temperature overnight protected from moisture, the red solution was poured into water; the colour changed to greenish-yellow with a pronounced blue fluorescence. The chloroform layer was separated, washed, dried, and evaporated under reduced pressure with gentle warming only. The residue crystallised from benzene–methanol, to give 5 : 6 : 11 : 12-tetrahydro-1 : 8-dimethoxychrysene (XIII; R = Me) (0·39 g.), m. p. (micro) 124—127°, identical with the substance described in the preceding paper.

(*b*) Substitution of ethanol (1 c.c.) for methanol in (*a*) (above) gave 1-ethoxy-5 : 6 : 11 : 12-tetrahydro-8-methoxychrysene (XIII; R = Et) (0·37 g.), m. p. (micro) 119—120°, identical with the substance obtained previously.

(*c*) Substitution of benzyl alcohol (1 c.c.) for methanol in (*a*) (above) afforded 1-*benzyloxy*-5 : 6 : 11 : 12-*tetrahydro*-4-*methoxychrysene* (XIII; R = CH_2Ph) (0·45 g.), m. p. (micro) 123—126°, separating as rods from benzene–methanol (Found: C, 84·9; H, 6·5. $C_{25}H_{24}O_2$ requires C, 84·8; H, 6·6%). Ultraviolet light absorption in hexane: $\lambda_{max.}$ 246 (infl.), 257, 270, 306 (infl.), 318, 332, and 348 (log ε 4·05, 3·77, 3·34, 4·23, 4·41, 4·50, and 4·33). Proof of the orientation of this substance was afforded by dehydrogenation with chloranil (3 equiv.) in boiling anisole for 6 hr., as described above in the case of the 1-methoxy-analogue (XIII; R = Me), to give 1-benzyloxy-8-methoxychrysene (XVIII; R = CH_2Ph), m. p. (micro) 159—161°,

identical with the compound prepared as above by benzylation of 1-hydroxy-8-methoxychrysene (XVIII; R = H).

(*d*) Substitution of glacial acetic acid (1 c.c.) for methanol in (*a*), and otherwise following the same procedure, gave *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-8-methoxy-1 : 4-dioxochrysene (II) (0·43 g.), identical with specimens prepared alternatively. This $\Delta^{15:16}$-diketone (II), when subjected to the treatment described in (*a*) (above), again gave 5 : 6 : 11 : 12-tetrahydro-1 : 8-dimethoxychrysene (XIII; R = Me).

(*e*) Omitting any added reagent after the saturation with hydrogen chloride, but otherwise following the procedure outlined in (*a*) (above), again gave *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-8-methoxy-1 : 4-dioxochrysene (II) (0·37 g.).

cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-1 : 1 : 8-*trimethoxy*-4-*oxochrysene* (XX; R = Me).—*cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-Decahydro-8-methoxy-1 : 4-dioxochrysene (II) (200 mg.) was dissolved in a few c.c. of boiling methanol with the aid of a few drops of benzene. To the boiling solution were added two drops of a saturated solution of hydrogen chloride in methanol, and the mixture was kept at the b. p. for 5 min., during which some concentration of the solution took place. On cooling, cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-1 : 1 : 8-*trimethoxy*-4-*oxochrysene* (180 mg.) separated as pale yellow plates, m. p. 134—138°, not changed on recrystallisation from methanol in the absence of acid; the compound was also recovered unchanged on recrystallisation from aqueous ethanol (Found: C, 73·6; H, 7·6; OMe, 27·1. $C_{21}H_{24}O_4$ requires C, 73·7; H, 7·7; 3OMe, 27·2%). The same result was obtained when *cis-syn*-1 : 2 : 3 : 4 : 5 : 6 : 12 : 13 : 14 : 15-decahydro-8-methoxy-1 : 4-dioxochrysene (I) was subjected to the same reaction conditions.

Reduction of cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-1 : 1 : 8-*trimethoxy*-4-*oxochrysene* (XX; R = Me) *with Lithium Aluminium Hydride.* cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*Decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XXI).—The above ketal (300 mg.) in tetrahydrofuran (15 c.c.) was added to lithium aluminium hydride (200 mg.) in tetrahydrofuran (10 c.c.), and the whole was heated under reflux for ½ hr. After cooling, the mixture was decomposed by ice and dilute sulphuric acid. The product was recovered in chloroform and evaporation gave a solid residue, crystallising from ethyl acetate–light petroleum to give cis-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-*decahydro*-4-*hydroxy*-8-*methoxy*-1-*oxochrysene* (XXI) as colourless plates (210 mg.), m. p. (micro) 192—193° (Found: C, 76·4; H, 7·8. $C_{19}H_{22}O_3$ requires C, 76·5; H, 7·6%). Ultraviolet light absorption: $\lambda_{max.}$ 274 mμ (log ε 4·14). This substance was mentioned but not characterised in the preceding communication; its structure was established by the two following experiments.

(*a*) The above hydroxy-ketone (XXI) (100 mg.) in tetrahydrofuran (15 c.c.) was added to lithium aluminium hydride (100 mg.) in tetrahydrofuran (10 c.c.), and the mixture was heated under reflux for ½ hr. The working-up procedure outlined immediately above afforded *cis*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-1 : 4-dihydroxy-8-methoxychrysene (60 mg.), m. p. (micro) 152—156°, identical with a specimen prepared by an alternative route (preceding paper).

(*b*) The hydroxy-ketone (XXI) (100 mg.) was heated under reflux with 5% ethanolic potassium hydroxide (20 c.c.) for ½ hr. After cooling and dilution with much water, the product was isolated with the aid of chloroform in the usual manner. Crystallisation from ethyl acetate–light petroleum gave *trans*-1 : 2 : 3 : 4 : 5 : 6 : 11 : 12 : 13 : 14-decahydro-4-hydroxy-8-methoxy-1-oxochrysene (XXII) (60 mg.), m. p. (micro) 174—175°, not depressed on admixture with a specimen prepared by an alternative route (see preceding paper).

The authors are indebted to Mr. W. A. L. Marshment for preparative assistance.

National Institute for Medical Research,
The Ridgeway, Mill Hill, London, N.W.7.

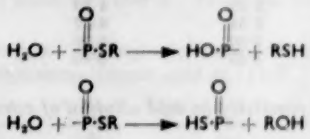
[*Received, April 20th*, 1956.

634. *The Hydrolysis of Diisopropyl Methylphosphonodithiolate.*

By R. F. Hudson and L. Keay.

Measurements of the rate of hydrolysis of di*iso*propyl methylphosphonodithiolate by estimation of acid and thio-compound produced show that P–S fission occurs both in acid and alkaline solution, which may be attributed to the low bond strength. This is reflected in the high reactivity in alkaline solution (*ca.* 10^4 times as reactive as di*iso*propyl methylphosphonate). The rate in acid solution is about 5 times less than that of the oxygen-ester, although in this case also a considerable decrease in activation energy is observed.

The position of bond fission in the hydrolysis of thiol esters may be determined by direct observations on the nature of the reaction products.[1] An elegant method for determining



the end products quantitatively, described by Bohme and Schran [2] in the hydrolysis of thiolacetates, consists of oxidising thiols and thio-acids with iodine to the corresponding disulphide and hydrogen iodide, and titrating this acid with alkali. Dialkyl phosphonothiolates are readily oxidised electrolytically and by halogens,[3] and other phosphoro- and phosphono-thiolates are oxidised similarly [4] by halogens:

$$2(RO)_2PO{\cdot}SH + I_2 = (RO)_2PO{\cdot}S{\cdot}S{\cdot}PO(OR)_2 + 2HI$$

Considering the two possible reaction mechanisms:

$$\begin{aligned} (a)\ & P{\cdot}SR + H_2O = P{\cdot}SH + ROH \\ & 2\,P{\cdot}SH + I_2 = P{\cdot}S{\cdot}S{\cdot}P + 2HI \\ (b)\ & P{\cdot}SR + H_2O = P{\cdot}OH + RSH \\ & 2RSH + I_2 = R{\cdot}S{\cdot}S{\cdot}R + 2HI \end{aligned}$$

It follows that one equivalent of acid is produced for each equivalent of iodine reduced if mechanism (*a*) is correct, but two equivalents of acid per equivalent of iodine if mechanism (*b*) is correct.

The results shown in Table 1 show clearly that the thiol and not the alcohol is produced in the reaction with hydroxyl ions, so that reaction proceeds at the phosphorus atom. Whereas methyl thiolacetate is slightly less reactive than methyl acetate,[5] di*iso*propyl methylphosphonodithiolate reacts $2{\cdot}5 \times 10^4$ times faster in alkali than the corresponding oxygen-ester (Table 3) with a corresponding decrease in activation energy. The decreased rate and increased activation energy of the reaction of methyl thiolacetate may be attributed to the reduced electronegativity of the sulphur atom, thus reducing the electrostatic attraction of the hydroxide ion:

$$R{\cdot}CO{\cdot}SR + OH^- \rightleftharpoons R{\cdot}C(OH)(SR){\cdot}O^- \longrightarrow R{\cdot}CO_2H + RS^-$$

This decrease in reactivity is opposed by the decrease in C–S bond strength (54 kcal. $mole^{-1}$) compared with the C–C bond energy (75 kcal. $mole^{-1}$).[6] For phosphonates the

[1] Morse and Tarbell, *J. Amer. Chem. Soc.*, 1952, **74**, 416; Stevens and Tarbell, *J. Org. Chem.*, 1954, **19**, 1996; Schaefgen, *J. Amer. Chem. Soc.*, 1948, **70**, 1308.
[2] Bohme and Schran, *Chem. Ber.*, 1949, **82**, 456.
[3] Foss, *Acta Chem. Scand.*, 1947, **1**, 8; *Kgl. norske Videnskab. Selskabs, Forhandl.*, 1942, **15**, 119.
[4] Malatesta and Pizzotti, *Chimica e Industria*, 1945, **27**, 6; *Gazzetta*, 1946, **76**, 167, 182.
[5] Rylander and Tarbell, *J. Amer. Chem. Soc.*, 1950, **72**, 3021.
[6] Neale and Williams, personal communication.

decrease in bond strength (95—100 to 45—50 kcal. mole^{-1}) [7] is so great as to cause a considerable increase in reactivity. The increase in the collision factor (PZ) accompanying the decrease in activation energy (Table 3) is interesting since the two Arrhenius parameters

TABLE 1. *The hydrolysis of diisopropyl methylphosphonodithiolate in* 0·2N-NaOH *at* 0°.

The reaction mixture (5 ml.) was quenched in potassium hydrogen phthalate (5 ml. ≡ 5·20 ml. of 0·178N-sodium hydroxide), oxidised by 10 ml. of iodine solution, and titrated against 0·1N-sodium thiosulphate.

Time (min.)	Titre of $Na_2S_2O_3$ (ml.)	Change in $Na_2S_2O_3$ titre, ΔT_1 (ml.)	Titre of NaOH (ml.)	Change in NaOH (0·1N) titre, ΔT_2 (ml.)	$\frac{\Delta T_2}{\Delta T_1}$
1	6·80	—	1·81	—	—
1·75	6·47	0·33	2·30	0·87	2·63
3·0	5·67	1·13	3·05	2·22	1·97
4·75	5·24	1·56	3·60	3·20	2·05
6·50	4·83	1·97	4·02	3·95	2·00
8·0	4·50	2·30	4·35	4·54	1·97
10·0	4·26	2·54	4·62	5·02	1·98
12·0	3·91	2·89	4·90	5·52	1·91
∞	2·40	4·40	6·40	8·20	1·87

TABLE 2. *The reactivity in acid solution of esters and thiolesters.*

	k	E (kcal. mole^{-1})	log PZ
Bu^t acetate	8·00 (30°)	23·2	13·6
Bu^t thiolacetate	0·82 (30°)	20·7	10·8
Pr$^i_2$ methylphosphonate	2·00 (110°)	25·6	11·4
Pr$^i_2$ methylphosphonodithiolate	0·46 (110°)	15·1	4·85

TABLE 3. *The reactivity in alkaline solution of esters and thiolesters.*

	k (l. mole^{-1} min.$^{-1}$)	E (kcal. mole^{-1})	log PZ
Me acetate	3·96 (20°)	12·2	9·7
Me thiolacetate	2·41 (20°)	13·1	10·2
Pr$^i_2$ methylphosphonate	0·55 (80°)	14·9	5·4
Pr$^i_2$ methylphosphonodithiolate	2·41 (25°)	11·4	7·3

frequently increase together,[8] as, for example, in the reaction of the corresponding carboxylic esters. The increased collision factor may be due to the greater covalent radius of the sulphur atom compared with the oxygen atom, which removes the bulky *iso*propyl groups further from the centre of substitution.

Measurements in acid solution showed that similarly the thiol and not the alcohol is produced (Table 4), so that substitution proceeds at the phosphorus atom, and not at the carbon atom as is probably the case in the reaction of the corresponding oxygen-ester. The activation energy of the reaction of the thiol-ester (15·1 kcal. mole^{-1}) is much less than that of the oxygen ester (25·6 kcal. mole^{-1}) and the PZ factor is also reduced considerably (Table 2). This is consistent with a change in mechanism from an S_N1 ionisation mechanism in the acid hydrolysis of the oxygen-ester, to a bimolecular substitution at the phosphorus atom. This change in mechanism is understandable since the P–S bond is very much weaker than the P–O bond and even weaker than the C–S bond. A similar change in mechanism has also been observed in the case of the acetates and thiolacetates of tertiary alcohols (Table 2). *tert.*-Butyl acetate hydrolyses, with alkyl–oxygen fission, by the S_N1 mechanism in acid solution,[9] whereas the thiol-ester is hydrolysed only one-tenth as fast with a reduced activation energy and PZ factor with acyl–sulphur fission.[5]

EXPERIMENTAL

Preparation of Diisopropyl Methylphosphonodithiolate.—Methylphosphonic dichloride (66 g.) in ether (200 ml.) was added dropwise with stirring and ice-cooling to propane-2-thiol (76 g.)

[7] Pauling "Nature of the Chemical Bond," Cornell Univ. Press, New York, 1940.
[8] Fairclough and Hinshelwood, *J.*, 1937, 538, 1573.
[9] Bunton, *Research*, 1951, **4**, 383; Stimson, *J.*, 1955, 2010.

and triethylamine (135 ml.) in ether (1 l.). Then the mixture was set aside at room temperature overnight. The precipitate was filtered off and washed with ether. The ether was removed from the combined filtrate and washings and the *ester* was distilled *in vacuo* (yield 72%; b. p. 94°/0·2 mm.) (Found: C, 39·8; H, 8·2. $C_7H_{17}POS_2$ requires C, 39·6; H, 8·1%).

Products of Hydrolysis.—Aliquot parts (5 ml.) of the reaction mixture were pipetted into flasks containing known volumes of standard iodine and hydrochloric acid. The excess of iodine was titrated with 0·1N-sodium thiosulphate solution with starch as indicator. When the blue colour just disappeared, phenolphthalein was added and the acid content determined by titration with standard sodium hydroxide. From these measurements the ratio of the equivalents of acid to iodine titrated was calculated for various stages of the reaction (Table 1).

In order to determine the amount of thiol produced on acid hydrolysis, 2·477 g. of the ester were refluxed for 40 hr. with 50 ml. of N-hydrochloric acid. The solvent was distilled off and the remainder made up to 100 ml. with distilled water. An aliquot part (5 ml.) of this solution was added to excess of iodine and back-titrated with 0·1N-thiosulphate. The 5 ml. aliquot part was equivalent to 5·79 ml. of iodine solution, therefore 1 mole of ester produces 0·99 mole of thiol. The kinetic results are given in Table 4. From the initial reading it would appear

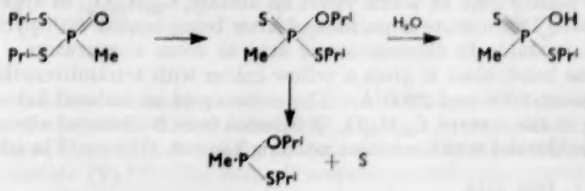
TABLE 4. *The hydrolysis of diisopropyl methylphosphonodithiolate in N-benzenesulphonic acid at 111·3°.*

Time (min.)	Titre of $Na_2S_2O_3$ (ml.)	Change in $Na_2S_2O_3$ titre, ΔT_1 (ml.)	Titre of NaOH (ml.)	Change in 0·1N-NaOH titre, ΔT_2 (ml.)	$\Delta T_2/\Delta T_1$	Reaction (%) from NaOH	Reaction (%) from $Na_2S_2O_3$
0	9·02	—	25·20	—	—	0	0
10	8·65	0·37	25·60	0·80	2·16	5·13	6·2
35	8·01	1·01	26·45	2·50	2·47	16·0	17·1
60	7·39	1·63	27·28	4·16	2·55	26·7	27·6
120	6·36	2·11	28·70	7·00	2·63	44·9	45·1
180	5·55	3·47	29·75	8·90	2·57	58·3	58·8
300	5·10	3·92	30·70	11·00	2·81	70·5	66·4
∞	3·12	5·90	33·0	15·60	2·65	—	—

TABLE 5. *Rate of hydrolysis of diisopropyl methylphosphonodithiolate.*

0·20N-NaOH			1·0N-$PhSO_3H$		
Temp.	[Ester]	k (l. mole^{-1} hr.$^{-1}$)	Temp.	[Ester]	k (hr.$^{-1}$)
0·0°	0·11	42·7	92·5°	0·20	0·200
5·0	0·08	59·6	100·1	0·25	0·338
10·0	0·08	80·5	109·4	0·20	0·464
14·0	0·09	110	113·3	0·25	0·556
25·0	0·08	241			

that thiol alone is released in the first stage, but the increasing ratio suggests that some further decomposition occurs as the reaction progresses. Although the ratio of acid to iodine reduced is greater than 2, the rates of reaction determined from the two series of estimations are very similar. This indicates that the increased ratio is caused by a side reaction in which sulphur is produced in a non-oxidisable form. Thiol-esters are known to be thermally labile, and sulphur was gradually precipitated on prolonged storage of the phosphonodithiolate. Since isomerisation also readily occurs in these systems the side reaction may proceed by a series of processes of the following kind:



QUEEN MARY COLLEGE,
MILE END ROAD, LONDON, E.1.

[*Received, October 19th,* 1955.]

635. *Triterpenoids. Part LIII.* The Constitution and Stereochemistry of Butyrospermol.*

By William Lawrie, William Hamilton, F. S. Spring, and H. S. Watson.

Oxidation of dihydrobutyrospermyl acetate with chromic acid gives 7-oxo*apo*euphenyl acetate, which is isomerised by mineral acid to 7-oxo*iso*euph-13(17)-enyl acetate (XIV). The latter is identified by its reduction, by the Wolff–Kishner method and reacetylation, to *iso*euph-13(17)-enyl acetate (VI), and by its oxidation with selenium dioxide to 7-oxo*iso*eupha-11 : 13(17)-dienyl acetate (XVI). Similar reduction of 7-oxo*apo*euphenyl acetate gives *apo*euphenyl acetate which is isomerised by hydrogen chloride to *iso*euph-13(17)-enyl acetate (VI); euph-8-enyl acetate is unchanged under the same acid treatment. Oxidation of 7-oxo*apo*euphenyl acetate with selenium dioxide gives an αβ-unsaturated ketone, 7-oxo*apo*euphadienyl acetate, which is isomerised by mineral acid to 7-oxo*iso*eupha-5 : 13(17)-dienyl acetate (XX). The formation of 7-oxo*apo*euphenyl acetate is shown to involve a molecular rearrangement, and of the two possible structures, (XII) and (XIII), for this compound the former is preferred. The conversion of dihydrobutyrospermyl acetate into 7-oxo*apo*euphenyl acetate (XII) proves that the double bond in the former is between $C_{(17)}$ and $C_{(8)}$. The methyl-group migration included in this conversion is considered to synchronise with oxidation at the 7 : 8-double bond and accordingly the reaction does not involve the $C_{(9)}$-hydrogen atom. It follows that the $C_{(9)}$-hydrogen atom in dihydrobutyrospermyl acetate has the same configuration (α) as that in *iso*euph-13(17)-enyl acetate, that the former compound is 9α-euph-7-en-3β-yl acetate (XI; R = Ac), and that butyrospermol is 9α-eupha-7 : 24-dien-3β-ol (XVII). Confirmation of structure (XVII) for butyrospermol is obtained from consideration of molecular-rotation relations. The euph-7-enyl acetate obtained by Wolff–Kishner reduction of 7-oxoeuph-8-enyl acetate, and reacetylation, is considered to be the 9β-epimer of dihydrobutyrospermyl acetate.

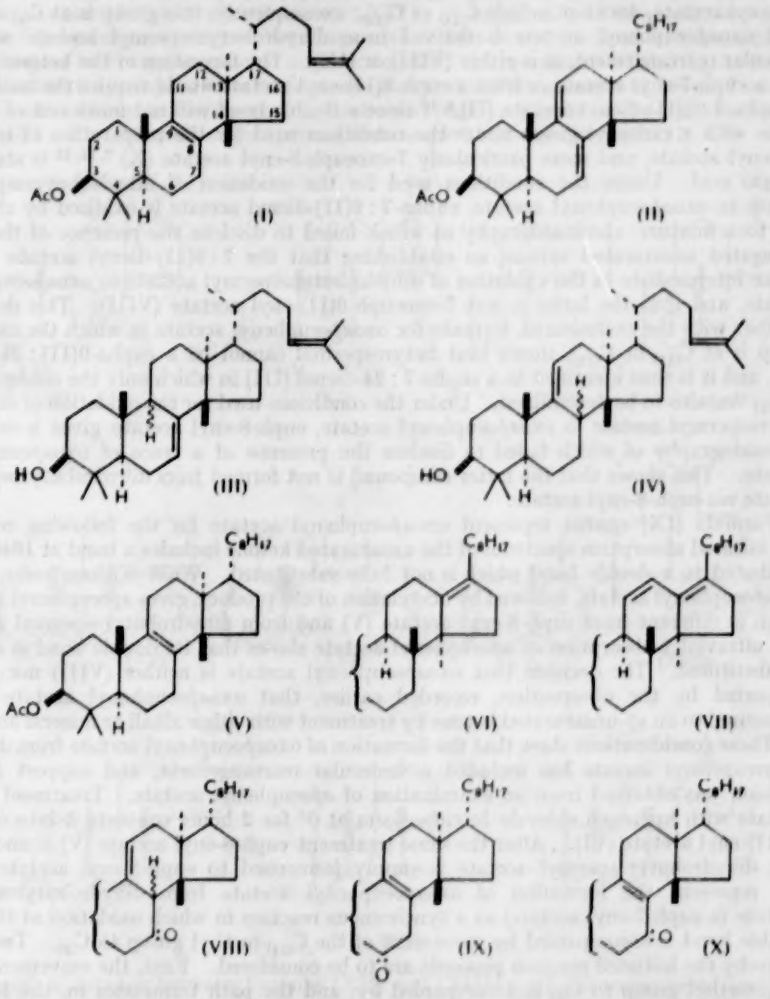
Addition of bromine to the side-chain double bond in butyrospermyl acetate, followed by isomerisation of the nuclear double bond with hydrogen chloride at 0°, and regeneration of the side-chain double bond with zinc, gives eupha-8 : 24-dienyl acetate (euphyl acetate) (I). Oxidation of dihydrobutyrospermyl acetate with osmic acid and acetylation of the product gives a saturated triol diacetate which is converted into eupha-7 : 9(11)-dienyl acetate (II) by mild heat. These observations led Irvine, Lawrie, McNab, and Spring [1,2] to the view that butyrospermol is either 9ξ-eupha-7 : 24-dien-3β-ol (III) or 8ξ-eupha-9(11) : 24-dien-3β-ol (IV). A similar decision has been reached by Jones and his collaborators [3,4] who, however, preferred the 9β-formulation of (III). The present paper describes experiments which show that butyrospermol is 9α-eupha-7 : 24-dien-3β-ol (XVII).

Oxidation of dihydrobutyrospermyl acetate, $C_{32}H_{54}O_2$, with chromic acid at 16° gives a mixture, chromatography of which yields an acetate, $C_{32}H_{52}O_3$, in approximately 25% conversion yield. This acetate is unchanged after being heated with pyridine and acetic anhydride and is stable to chromic–acetic acid at room temperature. It contains an isolated ethylene bond, since it gives a yellow colour with tetranitromethane, and shows absorption between 2000 and 2200 Å. The presence of an isolated keto-group in a six-membered ring in the acetate, $C_{32}H_{52}O_3$, is inferred from its infrared absorption spectrum (in carbon tetrachloride) which contains a strong band at 1710 cm.$^{-1}$ in addition to one at

* Part LII, *J.*, 1956, 2419.

[1] Irvine, Lawrie, McNab, and Spring, *Chem. and Ind.*, 1955, 626.
[2] *Idem*, *J.*, 1956, 2029.
[3] Dawson, Halsall, Jones, Meakins, and Phillips, *Chem. and Ind.*, 1955, 918.
[4] Jones and Halsall, "Fortschritte der Chemie organischer Naturstoffe," Springer-Verlag, 1955, Vol. XII, p. 108.

1735 cm.$^{-1}$ (acetate). The presence of a keto-group is also established by reactions described later. This non-conjugated unsaturated oxo-acetate which we name oxo*apo*euphenyl acetate, is not isomerised to an αβ-unsaturated ketone by treatment with either alkali or mineral acid. After treatment with alkali and reacetylation of the product, oxo*apo*euphenyl acetate is recovered. Hydrochloric–acetic acid converts oxo*apo*euphenyl



acetate into an isomeric non-conjugated unsaturated ketone, reduction of which, by the forcing variant of the Wolff–Kishner method,[5] followed by acetylation, gives *iso*euph-13(17)-enyl acetate (VI), identical with the product obtained by mineral-acid rearrangement of euph-8-enyl acetate (V).[6–8] The isomeric non-conjugated unsaturated ketone is thus

[5] Barton, Ives, and Thomas, *J.*, 1955, 2056.
[6] Vilkas, Dupont, and Dulou, *Bull. Soc. chim. France*, 1949, **16**, 813.
[7] Barton, McGhie, Pradhan, and Knight, *J.*, 1955, 876.
[8] Arigoni, Viterbo, Dünnenberger, Jeger, and Ruzicka, *Helv. Chim. Acta*, 1954, **37**, 2306; Ménard, Wyler, Hiestand, Arigoni, Jeger, and Ruzicka, *ibid.*, 1955, **38**, 1517.

an oxo*iso*euph-13(17)-enyl acetate in which the carbonyl oxygen is not attached to $C_{(12)}$. Oxidation of oxo*iso*euph-13(17)-enyl acetate with selenium dioxide gives an oxo*iso*eupha-11 : 13(17)-dienyl acetate which shows the same characteristic ultraviolet absorption spectrum as *iso*eupha-11 : 13(17)-dienyl acetate (VII), obtained by oxidation of *iso*euph-13(17)-enyl acetate (VI) with selenium dioxide.[7] The formation of oxo*iso*eupha-11 : 13(17)-dienyl acetate shows that the keto-group in oxo*iso*euph-13(17)-enyl acetate, and in oxo*apo*euphenyl acetate, does not include $C_{(11)}$ or $C_{(12)}$; consequently, this group is at $C_{(8)}$ or $C_{(7)}$.

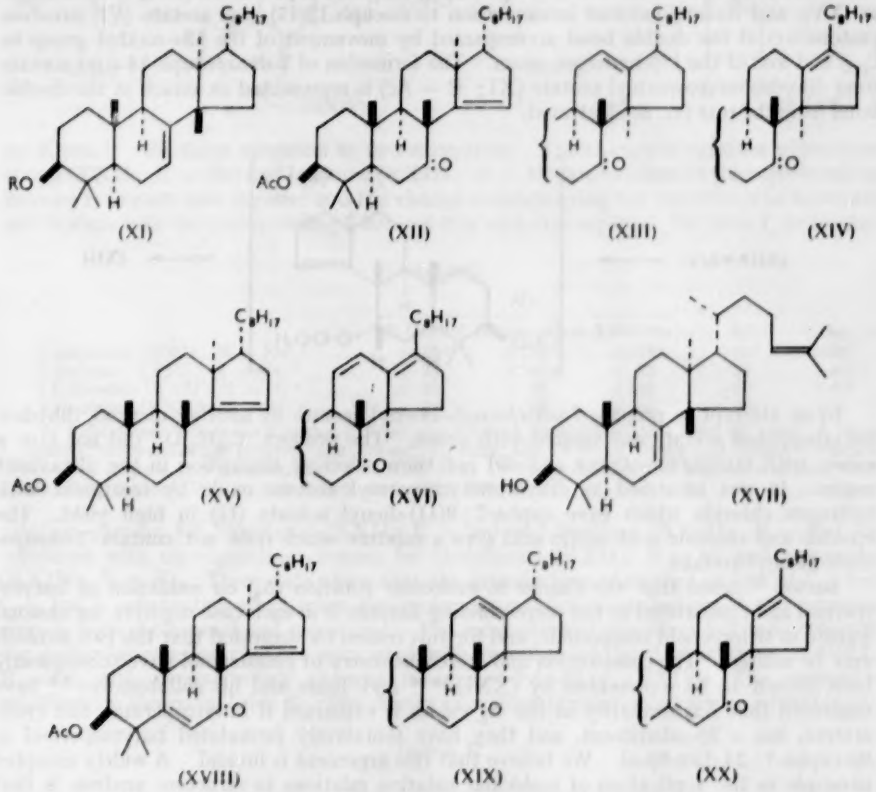
If oxo*apo*euphenyl acetate is derived from dihydrobutyrospermyl acetate without molecular rearrangement, it is either (VIII) or (IX). The formation of the ketone (VIII) from a euph-7-enyl acetate or from a euph-9(11)-enyl acetate would require the mediation of eupha-7 : 9(11)-dienyl acetate (II),[9,10] since a double bond will not move out of conjugation with a carbonyl group under the conditions used for the preparation of oxo*apo*euphenyl acetate, and more particularly 7-oxoeuph-8-enyl acetate (X) [7,11,12] is stable to mineral acid. Under the conditions used for the oxidation of dihydrobutyrospermyl acetate to oxo*apo*euphenyl acetate, eupha-7 : 9(11)-dienyl acetate is oxidised by chromic acid to a mixture, chromatography of which failed to disclose the presence of the non-conjugated unsaturated ketone, so establishing that the 7 : 9(11)-dienyl acetate (II) is not an intermediate in the oxidation of dihydrobutyrospermyl acetate to oxo*apo*euphenyl acetate, and that the latter is not 7-oxoeuph-9(11)-enyl acetate (VIII). This decision, together with the exclusion of formulæ for oxo*apo*euphenyl acetate in which the carbonyl group is at $C_{(11)}$ or $C_{(12)}$, shows that butyrospermol cannot be a eupha-9(11) : 24-dienol (IV), and it is thus identified as a eupha-7 : 24-dienol (III) in which only the configuration at $C_{(9)}$ remains to be determined. Under the conditions used for the oxidation of dihydrobutyrospermyl acetate to oxo*apo*euphenyl acetate, euph-8-enyl acetate gives a mixture, chromatography of which failed to disclose the presence of a trace of oxo*apo*euphenyl acetate. This shows that the latter compound is not formed from dihydrobutyrospermyl acetate *via* euph-8-enyl acetate.

Formula (IX) cannot represent oxo*apo*euphenyl acetate for the following reasons : The infrared absorption spectrum of the unsaturated ketone includes a band at 1640 $cm.^{-1}$ attributed to a double bond which is not fully substituted. Wolff–Kishner reduction of oxo*apo*euphenyl acetate, followed by acetylation of the product, gives *apo*euphenyl acetate, which is different from euph-8-enyl acetate (V) and from dihydrobutyrospermyl acetate. The ultraviolet absorption of *apo*euphenyl acetate shows that its double bond is at least trisubstituted. The decision that oxo*apo*euphenyl acetate is neither (VIII) nor (IX) is supported by the observation, recorded earlier, that oxo*apo*euphenyl acetate is not isomerised to an αβ-unsaturated ketone by treatment with either alkali or mineral acid.

These considerations show that the formation of oxo*apo*euphenyl acetate from dihydrobutyrospermyl acetate has included a molecular rearrangement, and support for this decision was obtained from an examination of *apo*euphenyl acetate. Treatment of this acetate with hydrogen chloride in chloroform at 0° for 2 hours converts it into *iso*euph-13(17)-enyl acetate (VI). After the same treatment euph-8-enyl acetate (V) is unchanged and dihydrobutyrospermyl acetate is simply isomerised to euph-8-enyl acetate (V).[1,2] We represent the formation of oxo*apo*euphenyl acetate from dihydrobutyrospermyl acetate (a euph-7-enyl acetate) as a synchronous reaction in which oxidation at the 7 : 8-double bond is accompanied by movement of the $C_{(14)}$-methyl group to $C_{(8)}$. Two paths whereby the initiated reaction proceeds are to be considered. First, the movement of the $C_{(14)}$-methyl group to $C_{(8)}$ is accompanied by, and the path terminates in, the loss of a proton from $C_{(15)}$. Following the second, the migration of the 14β-methyl group to $C_{(8)}$ is accompanied by migration of the 13α-methyl group to $C_{(14)}$ and loss of the 12β-hydrogen as a proton. Whichever path is followed, the carbonyl group in oxo*apo*euphenyl acetate is at $C_{(7)}$, and according to the first mechanism 7-oxo*apo*euphenyl acetate is (XII) and its conversion into 7-oxo*iso*euph-13(17)-enyl acetate (XIV), by treatment with mineral acid,

[9] Barbour, Bennett, and Warren, *J.*, 1951, 2540.
[10] Dawson, Halsall, and Swayne, *J.*, 1953, 590.
[11] McDonald, Warren, and Williams, *J.*, 1949, S155.
[12] Vilkas, *Bull. Soc. chim. France*, 1950, **17**, 582.

involves protonation of the 14 : 15-double bond, simultaneous movement of the 13α-methyl group to $C_{(14)}$ and loss of the 17β-hydrogen as a proton. If the second path is followed, 7-oxo*apo*euphenyl acetate is (XIII) and its subsequent isomerisation to 7-oxo*iso*-euph-13(17)-enyl acetate (XIV) is a simple carbonium-ion induced movement of the double bond from the 12- to the 13(17)-position. The oxo-dienyl acetate obtained by oxidation of 7-oxo*iso*euph-13(17)-enyl acetate (XIV) with selenium dioxide is represented as 7-oxo*iso*eupha-11 : 13(17)-dienyl acetate (XVI). A fundament of these mechanisms is that the $C_{(9)}$-hydrogen in dihydrobutyrospermyl acetate is not involved in the oxidation of this acetate to 7-oxo*apo*euphenyl acetate, *i.e.*, that the orientation of the $C_{(9)}$-hydrogen in dihydrobutyrospermyl acetate is the same (α) as that in 7-oxo*iso*euph-13(17)-enyl acetate (XIV). Accordingly we represent dihydrobutyrospermyl acetate as 9α-euph-7-en-3β-yl acetate (XI; R = Ac) and butyrospermol as 9α-euph-7 : 24-dien-3β-ol (XVII).



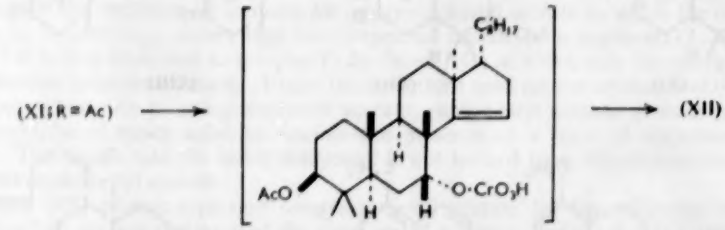
(XI) (XII) (XIII) (XIV)

(XV) (XVI) (XVII)

(XVIII) (XIX) (XX)

Although a decision between formulæ (XII) and (XIII) for 7-oxo*apo*euphenyl acetate is not pertinent to our argument concerning the structure and stereochemistry of butyrospermol, we favour the former alternative for the reasons discussed below. Oxidation of 7-oxo*apo*euphenyl acetate with selenium dioxide gives an αβ-unsaturated ketone, $C_{33}H_{50}O_3$, which shows an ultraviolet absorption maximum at 2350 Å (ε = 14,000) together with strong absorption in the ethylenic region. It gives a yellow colour with tetranitromethane and its infrared absorption spectrum, in Nujol, includes bands at 1735, 1240 (acetate), 1660 (αβ-unsaturated ketone), and 1634 cm.$^{-1}$ (isolated double bond). The oxidation of oxo*apo*euphenyl acetate with selenium dioxide has thus resulted in the introduction of a double bond in the 5 : 6-position, and the product is either (XVIII) or (XIX). Treatment

of the αβ-unsaturated oxo-acetate, $C_{32}H_{50}O_3$, with mineral acid converts it into an isomer which also shows the characteristic absorption spectrum of an αβ-unsaturated ketone ($\lambda_{max.}$ 2380 Å; $\varepsilon = 15{,}000$) together with strong absorption in the ethylenic region of the spectrum. This isomer is formed from the αβ-unsaturated ketone, (XVIII) or (XIX), by a mechanism similar to that operating the conversion of 7-oxo*apo*euphenyl acetate, (XII) or (XIII), into 7-oxo*iso*euph-13(17)-enyl acetate (XIV), and it is considered to be 7-oxo*iso*eupha-5 : 13(17)-dienyl acetate (XX). The fact that the double bond in 7-oxo*apo*euphenyl acetate is not attacked by selenium dioxide, supports the view that this compound is (XII) and not (XIII). This is also supported by the stability of the double bond in 7-oxo*apo*euphenyl acetate towards chromic acid which, if 7-oxo*apo*euphenyl acetate is (XIII), is difficult to reconcile with the ease with which the analogously constituted α-amyrin acetate and β-amyrin acetate are attacked by this oxidising agent. The product obtained by Wolff–Kishner reduction of 7-oxo*apo*euph-14-enyl acetate (XII) is formulated as (XV), and its acid-induced isomerisation to *iso*euph-13(17)-enyl acetate (VI) involves protonation of the double bond accompanied by movement of the 13α-methyl group to $C_{(14)}$ and loss of the 17β-hydrogen atom. The formation of 7-oxo*apo*euph-14-enyl acetate from dihydrobutyrospermyl acetate (XI; R = Ac) is represented as attack at the double bond from the rear (α), as illustrated.

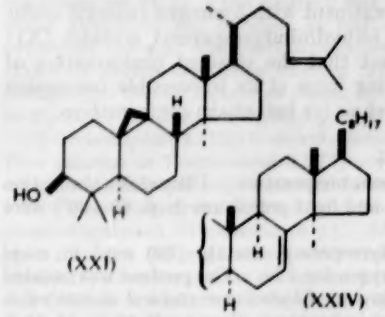


In an attempt to prepare 7-oxo*apo*euph-14-enyl acetate by another method, dihydrobutyrospermyl acetate was treated with ozone. The product, $C_{32}H_{54}O_3$, did not give a colour with tetranitromethane and did not show selective absorption in the ultraviolet region. It was identified as dihydrobutyrospermyl acetate oxide by treatment with hydrogen chloride which gave eupha-7 : 9(11)-dienyl acetate (II) in high yield. The epoxide and chromic acid–acetic acid give a mixture which does not contain 7-oxo*apo*euph-14-enyl acetate.

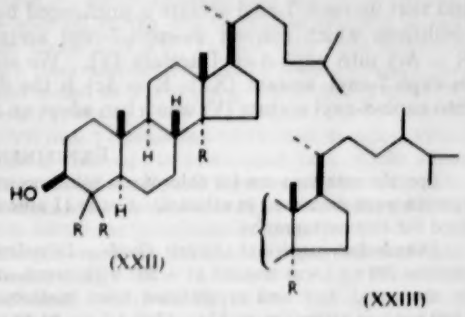
Barton [13] noted that the change in molecular rotation (Δ_3) on oxidation of butyrospermol and *cyclo*artenol to the corresponding ketones is in each case negative, an unusual feature in triterpenoid compounds, and for this reason he suggested that the two alcohols may be related. The constitution and stereochemistry of *cyclo*artenol have subsequently been shown to be represented by (XXI) [14–16] and Jones and his collaborators [3,4] have suggested that the similarity in the Δ_3 values is explained if butyrospermol, like *cyclo*artenol, has a 9β-substituent, and they have tentatively formulated butyrospermol as 9β-eupha-7 : 24-dien-3β-ol. We believe that this argument is invalid. A widely accepted principle in the application of molecular rotation relations to structure analysis is that terminal rings of the same type make contributions to the molecular rotation which are very approximately independent of the rest of the molecule, provided that the adjacent ring is a saturated unsubstituted *cyclo*hexane ring.[17,18] Another generally accepted principle is that nonangular methyl groups have little effect on the contribution of a terminal ring to the molecular rotation. Thus the change in molecular rotation (Δ_{00})

[13] Barton, *J.*, 1951, 1444.
[14] Bentley, Henry, Irvine, and Spring, *J.*, 1953, 3673.
[15] Barton, Page, and Warnhoff, *J.*, 1954, 2715.
[16] Irvine, Henry, and Spring, *J.*, 1955, 1316.
[17] Klyne, *J.*, 1952, 2916.
[18] Mills and Klyne in "Progress in Stereochemistry," Butterworths, London, Vol. I, p. 177.

consequent upon the introduction of a 3-carbonyl oxygen into many 5α-steroid and triterpenoid hydrocarbons is positive and the molecular-rotation change (Δ_3) accompanying the oxidation of a 3β-hydroxy-5α-steroid or of a 3β-hydroxy-triterpenoid to the corresponding ketone is also positive. Data illustrating these principles have been assembled



(XXI) (XXIV)



(XXII) (XXIII)

by Klyne.[17] We draw attention to two exceptions. The change in rotation when lanostanol (XXII; R = Me) and laudanol (XXIII; R = Me) are oxidised to the corresponding ketones is in each case *negative* and the change accompanying the conversion of lanostane and laudane into the corresponding 3-ketones is in each case *negative*. In Table 1, molecular-

TABLE 1.

	M_D				
	3β-Alcohol	Hydrocarbon	3-Ketone	Δ_3	Δ_{CO}
Lanostanol (XXII; R = Me) [a]	+150°	+149°	+116°	−34°	−33°
Laudanol (XXIII; R = Me) [b]	+ 93	+107	+ 62	−31	−45
Cholestanol (XXII; R = H) [c]	+ 93	+ 91	+159	+66	+68
Ergostanol (XXIII; R = H) [d]	+ 64	+ 66	+140	+76	+74

[a] From Voser, Montavon, Günthard, Jeger, and Ruzicka, *Helv. Chim. Acta*, 1950, **33**, 1893. [b] From Bentley, Henry, Irvine, Mukerji, and Spring, *J.*, 1955, 596. [c] From Fieser and Fieser, "Natural Products Related to Phenanthrene," Reinhold, 1949. [d] From Reindel and Walter, *Annalen*, 1928, **460**, 212; Reindel, Walter, and Rauch, *ibid.*, 1927, **452**, 34.

rotation changes for lanostanol (XXII; R = Me) and laudanol (XXIII; R = Me) are compared with corresponding changes for cholestanol (XXII; R = H) and ergostanol (XXIII; R = H). These data show that the introduction of methyl groups at $C_{(4)}$ and $C_{(14)}$ has a substantial effect upon the molecular-rotation contribution of the terminal rings in both cholestanol and ergostanol. The recognition of this effect led us to compare the molecular-rotation changes associated with reactions of dihydrobutyrospermol (XI; R = H) with corresponding changes for lanost-7-en-3β-ol (XXIV). The molecular rotations are shown in Table 2. The change in molecular rotation occurring when lanost-

TABLE 2.

	M_D						
	Alcohol	Acetate	Benzoate	Ketone	Δ_1	Δ_2	Δ_3
Lanost-7-en-3β-ol (XXIV) [a]	+45°	+156°	+266°	− 85°	+111°	+221°	−130°
Dihydrobutyrospermol (XI; R = H) [b]	−60	+ 56	+164	−182	+116	+224	−122

[a] From this paper. [b] From Heilbron, Jones, and Robins, *J.*, 1949, 444.

7-en-3β-ol is oxidised to lanost-7-en-3-one is *negative* and almost identical with that associated with the oxidation of dihydrobutyrospermol and butyrospermol to the corresponding 3-ketones. Moreover the Δ_1 (acetylation) and Δ_2 (benzoylation) values for lanost-7-en-3β-ol are nearly identical with the related values for dihydrobutyrospermol. This close correspondence supports the proposed steric formula (XVII) for butyrospermol.

We next consider the euph-7-enyl acetate obtained by Wolff–Kishner reduction of

7-oxoeuph-8-enyl acetate followed by acetylation of the product.[7] This preparative method establishes that this acetate has the more stable configuration at $C_{(9)}$ which must be β since the stereochemistry of 9α-euph-7-enyl acetate (dihydrobutyrospermyl acetate) (XI; R = Ac) constrains the molecule to adopt a conformation which includes a boat, whereas 9β-euph-7-enyl acetate can assume an all-chair (or half-chair) conformation. We find that 9β-euph-7-enyl acetate is unchanged by treatment with hydrogen chloride under conditions which convert 9α-euph-7-enyl acetate (dihydrobutyrospermyl acetate) (XI; R = Ac) into euph-8-enyl acetate (V). We suggest that the strained conformation of 9α-euph-7-enyl acetate (XI; R = Ac) is the driving force of its irreversible conversion into euph-8-enyl acetate (V) which can adopt an all-chair (or half-chair) conformation.

Experimental

Specific rotations are for chloroform solutions at room temperature. Ultraviolet absorption spectra were measured in ethanol. Grade II alumina and light petroleum (b. p. 60—80°) were used for chromatography.

Dihydrobutyrospermyl Acetate Oxide.—Dihydrobutyrospermyl acetate (250 mg.) in ethyl acetate (60 c.c.) was treated at −30° with ozonised oxygen for 1 hr. The product was isolated in the usual way and crystallised from methanol, giving *dihydrobutyrospermyl acetate oxide* (160 mg.) as plates, m. p. 154—155°, $[\alpha]_D$ −21·5° (*c* 1·0 in benzene) (Found: C, 78·8; H, 11·2. $C_{32}H_{54}O_3$ requires C, 79·0; H, 11·2%). The oxide does not show selective absorption between 2000 and 3000 Å. It does not give a colour with tetranitromethane in ethyl acetate, but its solution in chloroform containing this reagent gradually becomes deep yellow.

Eupha-7 : 9(11)-dienyl Acetate from Dihydrobutyrospermyl Acetate Oxide.—The oxide (35 mg.) in chloroform (5 c.c.) was treated with dry hydrogen chloride for 2 hr. The product was isolated in the usual way and its solution in light petroleum (25 c.c.) chromatographed on alumina (3 g.). Elution with light petroleum (50 c.c.) gave a fraction (23 mg.) which crystallised from methanol to give eupha-7 : 9(11)-dienyl acetate as needles, m. p. and mixed m. p. 110—111°, $\lambda_{max.}$ 2320, 2400, and 2470 Å (ε 16,000, 18,000, and 11,000).

7-*Oxo*apo*euph*-14-*enyl Acetate* (XII).—Dihydrobutyrospermyl acetate (2 g.) in methylene chloride (20 c.c.) and acetic acid (250 c.c.) was treated dropwise during 30 min. at room temperature with chromium trioxide (844 mg.) in acetic acid (70 c.c.). The mixture was kept at room temperature for 16 hr., a little methanol then added, and the mixture evaporated to dryness under reduced pressure. The gum, isolated with ether, was chromatographed in light petroleum (100 c.c.) on alumina (60 g.). Elution with light petroleum (1200 c.c.) gave fractions (total 442 mg.) which yielded dihydrobutyrospermyl acetate as prismatic needles (from chloroform–methanol), m. p. and mixed m. p. 134—135°. Elution with light petroleum–benzene (9 : 1, 1350 c.c.; then 4 : 1, 750 c.c.) gave fractions (450 mg.) each of which showed selective absorption between 2500 and 2700 Å. Crystallisation of these fractions gave (with large loss) 7-oxoeuph-8-enyl acetate as needles, m. p. and mixed m. p. 162—163°, $[\alpha]_D$ +40° ± 5° (*c* 0·4). Continued elution with light petroleum–benzene (1 : 1; 1500 c.c.) gave fractions (335 mg.), which crystallised from methanol to give 7-*oxo*apo*euph*-14-*enyl acetate* as stout needles, m. p. 119—120°, $[\alpha]_D$ −85° (*c* 1·0), ε_{2100} = 5400 (Found: C, 79·2; H, 11·1. $C_{32}H_{52}O_3$ requires C, 79·3; H, 10·8%). It gives a yellow colour with tetranitromethane and it is unchanged after treatment with acetic anhydride and pyridine at 100° for 1 hr. 7-Oxo*apo*euph-14-enyl acetate (100 mg.) in methylene chloride (1 c.c.)–acetic acid (30 c.c.) was treated dropwise during 15 min. with chromium trioxide (15 mg.) in acetic acid (3 c.c.), and the mixture kept at 20—25° for 24 hr. The chromium trioxide was not reduced and 7-oxo*apo*euph-14-enyl acetate, m. p. and mixed m. p. 118—120°, was recovered from the solution.

A solution of 7-oxo*apo*euph-14-enyl acetate (30 mg.) in 3% methanolic potassium hydroxide (10 c.c.) was refluxed for 2 hr. The hydrolysis product was isolated in the usual way and acetylated with acetic anhydride and pyridine for 1 hr. at 100°. The acetate was crystallised from methanol, yielding 7-oxo*apo*euph-14-enyl acetate (28 mg.) as needles, m. p. and mixed m. p. 119—120°.

7-*Oxo*iso*euph*-13(17)-*enyl Acetate* (XIV).—7-Oxo*apo*euph-14-enyl acetate (20 mg.) in concentrated hydrochloric acid–acetic acid (1 : 20; 2 c.c.) was kept at 100° for 3 hr. The product was isolated by means of ether and crystallised from methanol, yielding 7-*oxo*iso*euph*-13(17)-*enyl acetate* as plates, m. p. 112—113°, $[\alpha]_D$ −50° (*c* 1·3), ε_{2160} = 6700 (Found: 79·6; H, 11·0. $C_{32}H_{50}O_3$ requires C, 79·3; H, 10·8%). A mixture with 7-oxo*apo*euph-14-enyl acetate (m. p. 118—120°) had m. p. 93—105°. It gives a yellow colour with tetranitromethane in chloroform.

iso*Euph*-13(17)-*enyl Acetate* (VI) *from* 7-*Oxo*iso*euph*-13(17)-*enyl Acetate* (XIV).—The oxo-acetate (90 mg.) in diethylene glycol (10 c.c.) was mixed with a solution obtained by reaction of sodium (250 mg.) with diethylene glycol (15 c.c.), and the mixture heated to 200°. Anhydrous hydrazine was distilled in until the mixture refluxed at 180°. After refluxing for 18 hr. at 180°, the mixture was distilled until the temperature reached 210°, and refluxing was then continued for 24 hr. The product was isolated by means of ether, and acetylated by using acetic anhydride and pyridine at 100°. A solution of the dry acetylated product in light petroleum (25 c.c.) was chromatographed on alumina (5 g.). Elution with light petroleum (175 c.c.) gave a crystalline fraction (37 mg.) recrystallisation of which from methanol gave *iso*euph-13(17)-enyl acetate as plates, m. p. and mixed m. p. 110°, $[\alpha]_D$ −9° (*c* 2·0) (Found: C, 81·7; H, 11·7. Calc. for $C_{32}H_{54}O_2$: C, 81·6; H, 11·6%).

7-*Oxo*iso*eupha*-11 : 13(17)-*dienyl Acetate* (XVI) *from* 7-*Oxo*iso*euph*-13(17)-*enyl Acetate* (XIV).—To a solution of 7-oxo*iso*euph-13(17)-enyl acetate (140 mg.) in acetic acid (14 c.c.) was added selenium dioxide (80 mg.) dissolved in the minimum of water, and the mixture was refluxed for 3 hr. The product was isolated by means of ether and its solution in light petroleum (300 c.c.) chromatographed on alumina (6 g.). Elution with light petroleum–benzene (4 : 1; 350 c.c.) gave fractions (32 mg.) which were crystallised twice from methanol, giving 7-*oxo*iso*eupha*-11 : 13(17)-*dienyl acetate* as plates, m. p. 107—109°, $[\alpha]_D$ −44·5° ± 5° (*c* 0·2), $\lambda_{max.}$ 2470, 2550, and 2640 Å (ε 19,000, 21,000, and 14,500) (Found: C, 79·4; H, 10·45. $C_{32}H_{50}O_2$ requires C, 79·6; H, 10·4%). It gives a deep brown colour with tetranitromethane in chloroform.

apo*Euph*-14-*enyl Acetate* (XV).—7-Oxo*apo*euph-14-enyl acetate (125 mg.) was reduced by using the forcing Wolff–Kishner method described above. The product was isolated and acetylated by using standard procedures, and a solution of the dry acetylated product (130 mg.) in light petroleum (50 c.c.) chromatographed on alumina (4 g.). Elution with light petroleum (150 c.c.) gave a fraction (74 mg.) which, when crystallised twice from methanol, gave apo*euph*-14-*enyl acetate* as needles, m. p. 114—115°, $[\alpha]_D$ −12° (*c* 1·1), ε_{2150} = 5300 (Found: C, 81·5; H, 11·7. $C_{32}H_{54}O_2$ requires C, 81·6; H, 11·6%). A mixture with *iso*euph-13(17)-enyl acetate had m. p. 85—90°.

iso*Euph*-13(17)-*enyl Acetate* (VI) *from* apo*Euph*-14-*enyl Acetate* (XV).—*apo*Euph-14-enyl acetate (14 mg.) in dry chloroform (3 c.c.) was treated at 0° with a stream of dry hydrogen chloride for 2 hr. The product was isolated in the usual way and its solution in light petroleum (20 c.c.) filtered through alumina (3 g.). Light petroleum (200 c.c.) eluted a fraction (11·6 mg.) which crystallised from methanol to yield *iso*euph-13(17)-enyl acetate as plates, m. p. and mixed m. p. 109—110°, $[\alpha]_D$ −10° (*c* 0·4). A mixture with *apo*euph-14-enyl acetate (m. p. 114—115°) had m. p. 88—102°.

7-*Oxo*apo*eupha*-5 : 14-*dienyl Acetate* (XVIII).—A boiling solution of 7-oxo*apo*euph-14-enyl acetate (118 mg.) in acetic acid (4·8 c.c.) was treated dropwise with a solution of selenium dioxide (60 mg.) in the minimum of water and acetic acid (2 c.c.). The mixture was refluxed for 2 hr., the product isolated in the usual way, and its solution in light petroleum (25 c.c.) chromatographed on alumina (4 g.). The fractions (102 mg.), eluted with light petroleum (450 c.c.) and light petroleum–benzene (4 : 1; 200 c.c.), crystallised from methanol to give 7-*oxo*apo*eupha*-5 : 14-*dienyl acetate* as prisms, m. p. 103—104°, $[\alpha]_D$ −126° (*c* 1·2), $\lambda_{max.}$ 2350 Å ($\varepsilon_{max.}$ 14,100, ε_{2100} = 9000) (Found: C, 79·4; H, 10·4. $C_{32}H_{50}O_2$ requires C, 79·6; H, 10·4%). It gives a yellow colour with tetranitromethane.

7-*Oxo*iso*eupha*-5 : 13(17)-*dienyl Acetate* (XX).—7-Oxo*apo*eupha-5 : 14-dienyl acetate (217 mg.) in concentrated hydrochloric–acetic acid (1 : 20; 10 c.c.) was kept at 100° for 2 hr. The product (212 mg.), in light petroleum (25 c.c.), was chromatographed on alumina (4 g.). Elution with light petroleum and mixtures of light petroleum with up to 50% benzene gave fractions (158 mg.) which crystallised from methanol to give 7-*oxo*iso*eupha*-5 : 13(17)-*dienyl acetate* (105 mg.) as prisms, m. p. 119—120°, $[\alpha]_D$ −52° (*c* 2·1), $\lambda_{max.}$ 2080 and 2380 Å (ε 10,400 and 13,500) (Found: C, 79·3; H, 10·3. $C_{32}H_{50}O_2$ requires C, 79·6; H, 10·4%).

Lanost-7-enyl Acetate.—This was prepared by the method of Marker, Wittle, and Mixon;[19] it separates from methanol–ethyl acetate as plates, m. p. 144—145°, $[\alpha]_D$ +33·2° (*c* 2·6). Barton, Fawcett, and Thomas[20] give m. p. 145°, $[\alpha]_D$ +32°. Hydrolysis of the acetate, with lithium aluminium hydride, gave lanost-7-en-3β-ol (XXIV) as needles (from methanol–ethyl acetate), m. p. 157—158°, $[\alpha]_D$ +10·4° (*c* 1·5). Woodward *et al.*[21] give m. p. 162—163°, $[\alpha]_D$ +10°. Lanost-7-enyl benzoate was prepared from the alcohol in the usual way; it separates from

[19] Marker, Wittle, and Mixon, *J. Amer. Chem. Soc.*, 1937, **59**, 1368.
[20] Barton, Fawcett, and Thomas, *J.*, 1951, 3147.
[21] Woodward, Patchett, Barton, Ives, and Kelly, *J. Amer. Chem. Soc.*, 1954, **76**, 2852.

methanol as needles, m. p. 207—209°, $[\alpha]_D$ +50° (*c* 1·9). Woodward *et al.*[21] give m. p. 207—208°, $[\alpha]_D$ +51°.

Lanost-7-en-3-one.—A solution of lanost-7-en-3β-ol (2 g.) in pyridine (40 c.c.) was kept for 24 hr. at 16° with the complex prepared from chromium trioxide (2 g.) and pyridine (20 c.c.). The product was isolated in the usual way and crystallised from methanol–ether, giving lanost-7-en-3-one as blades, m. p. 146—147°, $[\alpha]_D$ −20° (*c* 2·8) (Found : C, 84·7; H, 12·0. Calc. for $C_{30}H_{50}O$: C, 84·4; H, 11·8%). Marker *et al.*[19] give m. p. 149°.

Ozonolysis of Euph-8-enyl Acetate.—Euph-8-enyl acetate (10·0 g.) in ethyl acetate (300 c.c.) was treated with a slow stream of ozone at −5° for 2 hr. After the solution had been washed with aqueous ferrous sulphate and sodium hydrogen carbonate solutions, the solvent was removed under reduced pressure and the product chromatographed on alumina (330 g.). Elution with light petroleum–benzene (1 : 1; 3·2 l.) and crystallisation from methanol gave crystals (490 mg.) repeated crystallisation of which yielded 11-oxoeuph-8-enyl acetate (128 mg.) as blades, m. p. and mixed m. p. 127—128°, $[\alpha]_D$ +26·2° (*c* 2·2), $\lambda_{max.}$ 2570 Å (log ε 3·93). Barton *et al.*[7] give m. p. 130—131°, $[\alpha]_D$ +28°, $\lambda_{max.}$ 2550 Å (log ε 3·99). Elution of the column with benzene–light petroleum (3 : 1, 4 l.) and benzene (4·8 l.), and four crystallisations from methanol gave 7-oxoeuph-8-enyl acetate (716 mg.) as needles, m. p. 163—165°, $[\alpha]_D$ +35·5° (*c* 1·4), $\lambda_{max.}$ 2540 Å (log ε 4·0).

9β-*Euph-7-enyl Acetate.*—7-Oxoeuph-8-enyl acetate (690 mg.) was reduced by using forcing Wolff–Kishner conditions as described by Barton *et al.*[7] The dry acetylated product in light petroleum was chromatographed on alumina (22 g.). Light petroleum (650 c.c.) eluted a fraction, crystallisation of which from acetone–methanol gave 9β-euph-7-enyl acetate (160 mg.) as blades, m. p. 78—79°, $[\alpha]_D$ −98° (*c* 0·4), $\varepsilon_{3060} = 3060$ (Found : C, 81·3; H, 11·5. Calc. for $C_{32}H_{54}O_2$: C, 81·6; H, 11·6%). It gives a pale yellow colour with tetranitromethane. Barton *et al.*[7] give m. p. 92—94°, $[\alpha]_D$ −60°.

9β-Euph-7-enyl acetate (113 mg.) in chloroform (15 c.c.) was treated at 0° with dry hydrogen chloride for 2 hr. From the solution 9β-euph-7-enyl acetate was recovered in good yield as blades, m. p. 76—78° (no depression), $[\alpha]_D$ −95° (*c* 0·9).

We thank the Department of Scientific and Industrial Research for a Maintenance Award (to W. L.) and Sir Alexander Cross and the Cross Trust for a Scholarship (to W. H.). We also thank Dr. Geoffrey Eglinton for the measurement and interpretation of the infrared absorption spectra and Dr. A. C. Syme and Mr. Wm. McCorkindale for the microanalyses.

The Royal Technical College, Glasgow. [*Received, March 15th,* 1956.]

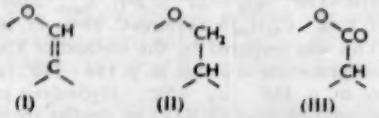
---

636. *Quassin and* neo*Quassin. Part IV.*[1]

By R. J. S. Beer, K. R. Hanson, and Alexander Robertson.

Like quassin and *neo*quassin, deoxoquassin, a dihydro-derivative of anhydro*neo*quassin, is readily demethylated, giving deoxonorquassin the properties and reactions of which are in agreement with the view that it is an enolic α-diketone.

Whereas anhydro*neo*quassin is converted by aqueous acetic acid into *neo*quassin and by methanolic hydrogen chloride into α- and β-*O*-methyl*neo*quassin,[1] the hydrogenation product of anhydro*neo*quassin, a dihydro-derivative formed with the aid of a Raney nickel catalyst, is stable to these reagents and has the same ultraviolet absorption as *neo*quassin. As it



(I) (II) (III)

is obviously formed by hydrogenation of the αβ-unsaturated ether residue (I) in anhydro-*neo*quassin this dihydro-compound contains the partial structure (II) and may conveniently be termed deoxoquassin since quassin is the corresponding lactone (III).

[1] Part III, Hanson, Jaquiss, Lamberton, Robertson, and Savige, *J.*, 1954, 4238.

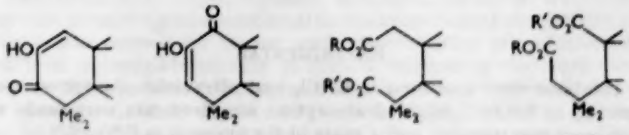
Starting with deoxoquassin, a number of experiments have been carried out, the results of which lend general support to the views expressed in Part III, particularly those which relate to chromophore (A). With hot dilute mineral acid deoxoquassin loses a methyl group, giving deoxonorquassin, analogous to norquassin and nor*neo*quassin. Deoxonorquassin behaves as an enol and can be remethylated with methanolic hydrogen chloride to deoxoquassin. In alkaline solution the ultraviolet absorption spectrum of deoxonorquassin shows a major peak attributed to chromophore (B) [1] and a minor peak at 314 mμ due to the enol ion derived from chromophore (A).

Oxidation of deoxonorquassin with alkaline hydrogen peroxide furnished a high yield of a non-enolic dibasic acid, $C_{20}H_{27}O_6 \cdot OMe$, the ultraviolet absorption of which is very similar to that of dihydroquassin. This spectrum is unchanged in alkaline solution and can therefore be attributed to chromophore (B).[1] Clearly, the dibasic acid is derived by oxidative fission of an α-diketone system, which is present in the enolic form in deoxonorquassin and as the enol ether (chromophore A) in deoxoquassin. Formulation of the enolic system as (IV) or (V), in agreement with previous results,[1] suggests for the dibasic acid partial structures (VI or VII; R = R′ = H), which are consistent with the behaviour of the acid on esterification. We shall employ formulæ (IV) and (VI) in subsequent discussion.

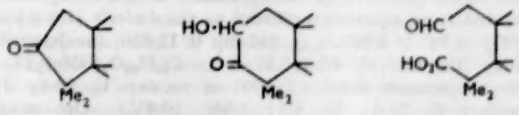
With diazomethane the dibasic acid gave rise to a dimethyl ester (VI; R = R′ = Me) whereas prolonged treatment with methanolic hydrogen chloride at room temperature gave only a monomethyl ester (A) (VI; R = Me, R′ = H). A second monomethyl ester (B) (VI; R = H, R′ = Me) is formed by mild hydrolysis of the dimethyl ester with alkali.

Attempts to convert the dibasic acid into a *cyclo*pentanone (VIII) by the action of heat were unsuccessful, giving only a neutral non-ketonic gum. Reduction of the dibasic acid with lithium aluminium hydride gave a non-crystalline product which had no significant ultraviolet absorption above 220 mμ, a result which supports the view that chromophore (B) is not a diene system but is an αβ-unsaturated ketone.

On reduction with zinc and acetic acid, deoxonorquassin is converted into an alkali-insoluble deoxodihydronorquassin (IX). As expected, this product has ultraviolet absorption characteristic of chromophore (B) and its infrared spectrum has a peak at 1710 cm.$^{-1}$ which may be attributed to a *cyclo*hexanone-carbonyl group. Periodate oxidation of



(IV) (V) (VI) (VII)



(VIII) (IX) (X)

dihydro-compound (IX) furnished an acid, presumably (X), which reacts immediately with Brady's reagent (the dihydro-compound reacts rather slowly with this reagent) and has infrared absorption peaks at 1737 (CHO group) and 1710 cm.$^{-1}$ (CO of CO_2H) and a broad shoulder at *ca.* 3050 cm.$^{-1}$ (CO_2H group).

The product obtained by reduction of deoxonorquassin with Raney nickel and hydrogen at room temperature and atmospheric pressure was amorphous but its properties clearly indicated that the enolic system derived from chromophore (A) had been reduced to a diol. Thus the reduction product was alkali-insoluble, gave no ferric reaction, and failed

to react with Brady's reagent, but was oxidised by sodium metaperiodate to a neutral non-crystalline substance which gave an immediate reaction with Brady's reagent.

Oxidation of deoxonorquassin by periodic acid yielded a non-enolic monobasic acid, $C_{20}H_{27}O_6 \cdot OMe$, and an enolic substance. The relation of these compounds to deoxonorquassin is not clear at present.

Deoxonorquassin is converted by the action of hot aqueous alkali into deoxonorquassinic acid, a reaction of the type previously encountered with nor- and nor*neo*-quassin, involving the addition of a molecule of water with the loss of the characteristic enol properties of the nor-compound. The ultraviolet absorption maxima of this acid and its methyl ester fall within the range 257—259 mμ already quoted for the analogous acids and esters derived from norquassin and nor*neo*quassin.[1] Methyl deoxonorquassinate has also been prepared from methyl nor*neo*quassinate by dehydration to methyl anhydronor*neo*quassinate and subsequent hydrogenation. The infrared absorption spectra of methyl anhydronor*neo*-quassinate and methyl deoxonorquassinate show sharp hydroxyl bands at 3440 and 3390 cm.$^{-1}$ respectively, thus providing further evidence that the conversion of the enolic nor-compounds into non-enolic acids with alkalis involves a transformation of the benzilic acid type. The newly formed hydroxyl group in these products is unreactive; thus *p*-nitrobenzazide is without action on methyl deoxonorquassinate and only the hemiacetal systems of nor*neo*quassinic acid and its methyl ester are readily oxidised by alkaline potassium permanganate and chromic acid respectively. Methyl deoxonorquassinate is also unaffected by dehydrating agents, *e.g.*, hot acetic anhydride and sodium acetate. Deoxonorquassinic acid is, however, oxidised by lead tetra-acetate at room temperature, giving a neutral non-crystalline product which reacts with Brady's reagent.

As in the conversion of norquassinic acid into the enolic *iso*bisnorquassinic acid [1] treatment of deoxonorquassinic acid with hot mineral acid gave a non-crystalline acid, deoxo*iso*bisnorquassinic acid, which with diazomethane affords a crystalline enolic methyl ester but on treatment with dimethyl sulphate and alkali gives the non-enolic methyl deoxonorquassinate. The latter reaction and the methylation experiments with *iso*-bisnorquassinic acid described in Part III [1] suggest that the *iso*bisnor-acids and the nor-acids are simply related as enols and enol ethers, but the considerable differences in the positions of the ultraviolet absorption maxima in the two series (nor-acid series, $\lambda_{max.}$ 257—259 mμ; *iso*bisnor-acid series, $\lambda_{max.}$ *ca.* 284 mμ) are then difficult to explain.

Experimental

Molecular rotations were measured in $CHCl_3$ and ultraviolet absorption spectra (Unicam spectrophotometer) in EtOH. Infrared absorption measurements were made with a Grubb-Parsons double-beam spectrometer and a paste of the material in "Nujol."

The light petroleum used had b. p. 60—80°.

Deoxoquassin.—Reduced in methanol (50 ml.) with hydrogen at room temperature and atmospheric pressure in the presence of Raney nickel, anhydro*neo*quassin (2 g.) gave deoxoquassin which separated from aqueous methanol as the *hydrate* (1·6 g.) in colourless needles, m. p. 187—188°, $[M]_D^{22}$ +74° (*c* 1·00), $\lambda_{max.}$ 256 mμ (ε 12,630) (unchanged in 0·04% alcoholic potassium hydroxide) [Found: C, 67·3; H, 8·3. $C_{20}H_{24}O_3(OMe)_2,H_2O$ requires C, 67·3; H, 8·2. Found, in a specimen dried at 100° *in vacuo*: C, 70·4; H, 8·2; OMe, 16·5. $C_{20}H_{24}O_3(OMe)_2$ requires C, 70·5; H, 8·1; OMe, 16·6%]. Deoxoquassin was recovered unchanged after treatment with boiling acetic acid (8 hr.), boiling aqueous acetic acid (3 hr.), cold 5% methanolic hydrogen chloride (3 days), or with boiling aqueous-methanolic sodium hydroxide (2 hr.).

Deoxonorquassin.—Deoxoquassin (1 g.) was heated under reflux with a mixture of acetic acid (4 ml.), concentrated hydrochloric acid (4 ml.), and water (32 ml.) for 3 hr. and the hot colourless solution was decanted from undissolved oil and allowed to cool; deoxonorquassin separated in colourless needles (0·5 g.), m. p. 160—164°. The combined mother-liquor and the solidified oil were heated for 2 hr. and on cooling gave a second crop of crystals (0·25 g.), m. p. 159—162°. Recrystallised from aqueous methanol and then from ethyl acetate–light petroleum, *deoxonorquassin* formed colourless prisms and hexagonal plates, m. p. 164—165°, $[M]_D^{22}$ +126° (*c* 1·00), $\lambda_{max.}$ 257 mμ (ε 11,900) [254 mμ (ε 8500), 314 (ε 4200) in 0·04% alcoholic

potassium hydroxide] (Found : C, 69·7; H, 8·0; OMe, 8·6. $C_{20}H_{28}O_4$·OMe requires C, 69·9; H, 7·8; OMe, 8·6%). This product, which is readily soluble in aqueous sodium hydroxide but not in aqueous sodium hydrogen carbonate, has a deep violet-brown ferric reaction, reacts immediately with Brady's reagent, and gives a red precipitate with diazotised *p*-toluidine. On treatment with methyl sulphate and alkali, or with methanolic hydrogen chloride for 4 days at room temperature, deoxonorquassin yielded deoxoquassin hydrate, m. p. and mixed m. p. 187—188°.

With acetic anhydride (4 ml.), containing a trace of pyridine, at room temperature for 7 days deoxonorquassin (0·3 g.) was converted into the *acetate* (0·25 g.) which, on crystallisation from aqueous methanol and then from benzene–light petroleum, formed flat needles, m. p. 215—216°, $\lambda_{max.}$ 240 mμ (ε 12,000) [Found : C, 68·6; H, 7·4; OMe, 7·7. $C_{22}H_{30}O_6$·OMe requires C, 68·6; H, 7·5; OMe, 7·7%]. The acetate, which had a negative ferric reaction, was readily hydrolysed with a hot dilute aqueous acetic acid solution of hydrochloric acid, giving deoxonorquassin.

Prepared with hydroxylamine hydrochloride and sodium acetate in hot aqueous methanol, the *oxime* of deoxonorquassin crystallised from aqueous methanol and then from ethyl acetate–light petroleum in colourless plates, m. p. 235—238° (decomp.), $\lambda_{max.}$ 249 mμ (ε 11,700) (Found : C, 67·6; H, 8·3; N, 3·8. $C_{21}H_{29}O_5N$ requires C, 67·2; H, 7·8; N, 3·7%).

Dibasic Acid from Deoxonorquassin.—To a solution of deoxonorquassin (0·5 g.) in ethanol (50 ml.) at 70°, a mixture of hydrogen peroxide (3 ml.; 100-vol.) and 2N-aqueous sodium hydroxide (6 ml.) was added portion-wise during 1 hr. After the addition of water (15 ml.), most of the ethanol was removed by distillation and the residual alkaline solution neutralised with concentrated hydrochloric acid, precipitating the *dibasic acid* as a white solid (0·5 g.), m. p. 280—282°. Recrystallised from aqueous methanol and then chloroform–light petroleum this acid formed colourless needles, m. p. 288—289°, which had a negative ferric reaction and did not react with diazotised *p*-toluidine; $[M]_D^{20}$ −319° (*c* 0·20), $\lambda_{max.}$ 253 mμ (ε 8900) (unchanged in alcoholic potassium hydroxide) (Found : C, 63·9; H, 7·6; OMe, 7·7%; equiv. wt., by titration, 206. $C_{20}H_{27}O_6$·OMe requires C, 63·9; H, 7·7; OMe, 7·6%; equiv. wt., 197). A solution of the acid (0·2 g.) in 2·5% methanolic hydrogen chloride (10 ml.), which had been kept at room temperature for 5 days, yielded an acidic *monomethyl ester* (A), which crystallised from aqueous methanol in hexagonal prisms (0·1 g.), m. p. 150—153°, $\lambda_{max.}$ 253 mμ (ε 9000) [Found : C, 64·8; H, 8·1; OMe, 14·7. $C_{20}H_{24}O_5(OMe)_3$ requires C, 64·7; H, 7·9; OMe, 15·2%]. On treatment of the acid (0·2 g.) in a little methanol with an excess of ethereal diazomethane for 30 min., the main product was a neutral *dimethyl ester* (0·1 g.), m. p. 80—82°, $\lambda_{max.}$ 254 mμ (ε 9000) [Found : C, 65·3; H, 8·0; OMe, 21·8. $C_{20}H_{25}O_4(OMe)_3$ requires C, 65·3; H, 8·1; OMe, 22·0%]. A solution of this ester (from 0·1 g. of dibasic acid) in a mixture of methanol (10 ml.) and 2N-aqueous sodium hydroxide was warmed for 10 min. and, after isolation with chloroform, the product was separated from a negligible amount of neutral material in the usual way. The acidic monomethyl ester (B) separated from aqueous methanol as a *hydrate* in rectangular plates, m. p. 90—92° [Found : C, 61·2; H, 7·8; OMe, 14·5. $C_{20}H_{25}O_5(OMe)_2.H_2O$ requires C, 62·0; H, 8·0; OMe, 14·5%]. Heated in nitrogen at 280° for 1 hr., the dibasic acid gave a brown non-ketonic gum which did not yield a crystalline product. Treatment of the dimethyl ester (from 0·4 g. of dibasic acid) with excess of lithium aluminium hydride (0·5 g.) in boiling ether for 2 hr. furnished a colourless gum with no significant ultraviolet absorption.

Deoxodihydronorquassin.—To a solution of deoxonorquassin (0·5 g.) in boiling acetic acid (10 ml.), zinc dust (1·0 g.) was added in four equal portions at intervals of 15 min. 45 Min. later the hot reaction mixture was filtered, the solid was washed with methanol and water, the combined filtrate and washings were extracted with chloroform, and the extract was freed from acidic material with 2N-aqueous sodium hydroxide and evaporated. Crystallised from ethyl acetate–light petroleum, the residue gave *deoxodihydronorquassin* in needles (0·2 g.), m. p. 240—245°, unchanged by further recrystallisation, $\lambda_{max.}$ 252 mμ (ε 8200) (Found : C, 69·4; H, 8·3; OMe, 8·6. $C_{20}H_{27}O_4$·OMe requires C, 69·6; H, 8·3; OMe, 8·6%). This compound reacted slowly with Brady's reagent and gave a negative ferric reaction.

Sodium metaperiodate (0·5 g.), in water (20 ml.), was added to a solution of deoxodihydronorquassin (0·3 g.) in methanol (10 ml.) and the mixture kept at 0° for 12 hr. On isolation with chloroform, the product was separated into a neutral and a main acidic fraction which on crystallisation from aqueous methanol slowly gave the *aldehydo-acid* (0·1 g.), m. p. 166—170°. Recrystallised from ethyl acetate–light petroleum, this had m. p. 176—178°, $\lambda_{max.}$ 253 mμ (ε 8300), and gave an immediate precipitate with Brady's reagent (Found : OMe, 8·2. $C_{20}H_{27}O_5$·OMe requires OMe, 8·2%).

When a solution of deoxonorquassin (0·2 g.) in methanol (50 ml.) containing Raney nickel was shaken with hydrogen at room temperature and atmospheric pressure the absorption of hydrogen almost ceased after 20 min. The product was a colourless gum, which was insoluble in aqueous sodium hydroxide, had a negative ferric reaction, failed to react with Brady's reagent and, on oxidation with sodium metaperiodate by the method used for deoxodihydronorquassin, gave a colourless amorphous product having ketonic properties.

Oxidation of Deoxonorquassin with Periodic Acid.—Sodium metaperiodate (0·5 g.) in 2N-sulphuric acid (10 ml.) was added to a solution of deoxonorquassin (0·5 g.) in methanol (10 ml.) at 0°. 2 Hours later the mixture was diluted with water (50 ml.) and the product isolated with chloroform and separated into neutral, " phenolic," and acidic fractions in the usual way. Acidification of a solution of the acidic fraction in aqueous sodium hydrogen carbonate gave an *acid* (0·15 g.), m. p. 175—178°, which separated from ethyl acetate–light petroleum in needles, m. p. 175—178°, with a negative ferric reaction (mixed m. p. with aldehydo-acid, m. p. 176—178°, from deoxodihydronorquassin was 150—165°), $\lambda_{max.}$ 256 mμ (ε 8700) (Found: C, 63·8; H, 7·3; OMe, 7·9%; equiv. wt., by titration, 397. $C_{20}H_{27}O_6$·OMe requires C, 63·9; H, 7·7; OMe, 7·9%; *M*, 394·5). This acid did not react with diazotised *p*-toluidine. Prepared with diazomethane, the methyl ester formed needles, m. p. 182—183°, from ethyl acetate–light petroleum [Found: OMe, 15·2. $C_{20}H_{24}O_3(OMe)_3$ requires OMe, 15·2%].

The " phenolic " fraction from the foregoing oxidation yielded an enolic substance, m. p. *ca.* 210°, which has not yet been characterised.

Deoxonorquassinic Acid.—A solution of deoxonorquassin (0·3 g.) in aqueous 2N-sodium hydroxide (30 ml.) was boiled for 3 hr., cooled, and acidified with concentrated hydrochloric acid. Isolated with chloroform, the product was crystallised from aqueous methanol and treated in sodium hydrogen carbonate solution with charcoal, giving *deoxonorquassinic acid* which separated from ethyl acetate–light petroleum in colourless prisms, m. p. 194—196°, $[M]_D^{22}$ −90° (*c* 1·00), pK_a 4·90, $\lambda_{max.}$ 258 (ε 8750) [253 mμ (ε 9000) in 0·04% alcoholic potassium hydroxide] (Found: C, 66·4; H, 8·1; OMe, 8·1%; equiv. wt., by titration, 360. $C_{20}H_{27}O_6$·OMe requires C, 66·6; H, 8·0; OMe, 8·2%; *M*, 378·5). This acid, which had a negative ferric reaction and did not react with diazotised *p*-toluidine, gave *methyldeoxonorquassinate* with ethereal diazomethane, rhombs, m. p. 225° (from benzene–light petroleum), $[M]_D^{22}$ −66° (*c* 1·00), $\lambda_{max.}$ 259 mμ (ε 8550) [Found: C, 67·3; H, 8·2; OMe, 15·9. $C_{20}H_{24}O_4(OMe)_3$ requires C, 67·3; H, 8·2; OMe, 15·8%]. This ester, which was also prepared from deoxonorquassinic acid with methyl sulphate and alkali and with methanolic hydrogen chloride, regenerated the parent acid on hydrolysis with hot dilute methanolic sodium hydroxide.

*Methyl Anhydronor*neo*quassinate.*—A mixture of methyl nor*neo*quassinate (0·5 g.), sodium acetate (0·2 g.), and acetic anhydride (5 ml.) was heated under reflux for 2½ hr., cooled, and diluted with methanol (10 ml.). After distillation of the excess of methanol and methyl acetate the residue was treated with 2N-aqueous sodium hydroxide, and the granular buff product was purified in benzene with aluminium oxide. Recrystallised from ethyl acetate–light petroleum, the resulting *methyl anhydronor*neo*quassinate* formed plates (0·25 g.), m. p. 192—194°, $\lambda_{max.}$ 258 mμ (ε 7540) [Found: C, 67·7; H, 7·8; OMe, 15·7. $C_{20}H_{24}O_4(OMe)_3$ requires C, 67·6; H, 7·7; OMe, 15·9%]. Hydrogenation of this ester (0·1 g.) in methanol (30 ml.) with a Raney nickel catalyst at room temperature for 3 hr. gave methyl deoxonorquassinate (0·08 g.), m. p. and mixed m. p. 224°.

*Methyl Deoxoiso*bisnorquassinate.—The solution formed by heating deoxonorquassinic acid (0·5 g.), acetic acid (8 ml.), and concentrated hydrochloric acid (8 ml.) under reflux for 8 hr. was diluted with water (50 ml.) and extracted with chloroform, giving an amorphous product with a green-black ferric reaction. With ethereal diazomethane this gave *methyl deoxoiso*bisnorquassinate (0·4 g.) which separated from ethyl acetate–light petroleum and then aqueous methanol in hexagonal prisms, m. p. 204°, $\lambda_{max.}$ 284 mμ (ε 8500) [340 mμ (ε 5810) in 0·75% alcoholic potassium hydroxide] (Found: C, 66·4; H, 8·2; OMe, 8·3. $C_{20}H_{27}O_6$·OMe requires C, 66·6; H, 8·0; OMe, 8·2%). This ester gave an intense green-black ferric reaction in aqueous alcohol. Methylation of the amorphous deoxo*iso*bisnorquassinic acid with methyl sulphate in 2N-aqueous sodium hydroxide furnished methyl deoxonorquassinate, m. p. and mixed m. p. 223°.

UNIVERSITY OF LIVERPOOL.

[*Received, March 26th,* 1956.]

637. *The Interaction of Boron Trichloride with Unsaturated Alcohols and Ethers.*

By W. Gerrard, M. F. Lappert, and H. B. Silver.

Interaction of unsaturated alcohols (allyl, methallyl) (1, 2, and 3 mols., severally) with boron trichloride (1 mol.) gave the appropriate dichloroboronites, chloroboronates, and trialkenyl orthoborates. The alkenyloxyboron chlorides, which were also obtained from the borates and boron trichloride, were unstable, decomposing to the appropriate chloroalkene, but stable 1 : 1 and 1 : 2 complexes were obtained with pyridine. Neither these borates nor tripropynyl borate was attacked by hydrogen chloride at 20°, but at 120° triallyl borate was dealkylated. Dealkylation by both hydrogen bromide and hydrogen iodide was accompanied by addition. Diallyl and dimethallyl ethers were easily cleaved by boron trichloride; the mixed allyl methallyl ether reacted by methallyl–oxygen fission. Neither ammonia nor pyridine co-ordinated with trialiyl borate, and the reaction with bromine was slow. General resemblance to saturated systems has been noted.

Studies [1] on boron trichloride–alcohol and –ether systems have been extended to unsaturated compounds. The reactions of allyl and methallyl alcohols and their mixed and simple ethers and of propynol show a broad similarity to those of corresponding saturated systems, except that certain reactions are accompanied by addition. The allyl and the methallyl group appear to have reactivities intermediate between those of *sec.*- and *tert.*-alkyl groups.

Triallyl borate,[2] obtained in poor yield, is the only borate previously prepared by the interaction of boron trichloride and an unsaturated alcohol, although the preparation of triallyl [3] and trimethallyl [4] borate from other starting materials has been described.

Allyl, methallyl, and propynyl orthoborate have now been prepared in good yield by addition of boron trichloride (1 mol.) to the appropriate alcohol (3 mols.) in *n*-pentane at −80°; the reverse order of addition was less successful. By alteration of the relative proportions of the reagents evidence of the formation of intermediate alkenyloxyboron chlorides was obtained:

$$BCl_3 \longrightarrow RO{\cdot}BCl_2 \longrightarrow (RO)_2BCl \longrightarrow B(OR)_3$$

Of the alkenyloxyboron chlorides, the dichloroboronites, $RO{\cdot}BCl_2$, could not be adequately characterised owing to their instability, but stable 1 : 2 complexes with pyridine, and in the allyl system also a 1 : 1 complex, were obtained. The chloroboronates, $(RO)_2BCl$, whilst still unstable, were not as easily decomposed as the dichloroboronites; a 1 : 2 complex with pyridine was obtained from diallyl chloroboronate, whilst the dimethallyl compound afforded a 1 : 1 complex. The alkenyloxyboron chlorides were also obtained from the appropriate orthoborate and boron trichloride; their decomposition followed the general scheme observed earlier in saturated systems: [1b, 5, 6]

$$B(OR)_3 \xrightarrow{BCl_3} (RO)_2B{\cdot}Cl \xrightarrow{BCl_3} RO{\cdot}BCl_2$$

$$3RO{\cdot}BCl_2 \longrightarrow 3RCl + B_2O_3 + BCl_3$$

$$3(RO)_2BCl \longrightarrow 3RCl + B_2O_3 + B(OR)_3$$

Pyrolysis of the 1 : 1 complex between allyl dichloroboronite and pyridine was similar to that observed with the *n*-butyl analogue,[7] whilst the 1 : 1 complex between dimethallyl

[1] Gerrard and Lappert, *J.*, 1951, (*a*) 1020; (*b*) 2545; (*c*) 1952, 1486; Edwards, Gerrard, and Lappert, *J.*, 1955, 1470.
[2] Councler, *J. prakt. Chem.*, 1871, **18**, 371.
[3] Rothstein and Saville, *J.*, 1952, 2987.
[4] Thomas, *J.*, 1946, 882.
[5] Gerrard and Lappert, *J.*, 1955, 3084.
[6] Lappert, *J.*, 1956, 1768.
[7] *Idem*, *J.*, 1953, 667.

chloroboronate and pyridine disproportionated to give the 1 : 2 dichloroboronite complex. Such a complex was also obtained from triallyl borate, boron trichloride, and pyridine, the chloro-ester being added to pyridine in excess to enhance the formation of the 1 : 2 complex.

Like most other orthoborates, the unsaturated ones are hydrolysed readily to give orthoboric acid and the appropriate alcohol. Neither with ammonia nor with pyridine was there evidence for co-ordination with triallyl borate (cf. Colclough, Gerrard, and Lappert [8] for orthoborate co-ordination reactions):

$$RO{\cdot}BCl_2{,}py \longrightarrow RCl + BOCl{,}py$$

$$2(RO)_2BCl{,}py \longrightarrow RO{\cdot}BCl_2{,}2py + B(OR)_3$$

$$B(OR)_3 + 2BCl_3 \longrightarrow 3RO{\cdot}BCl_2 \xrightarrow{6py} 3(RO{\cdot}BCl_2{,}2py)$$

Whereas trialkyl borates, except those possessing a very reactive α-carbon atom, such as tri-*tert.*-butyl borate (which is dealkylated instantly at room temp.), do not react with hydrogen chloride,[1b] triallyl, trimethallyl, and tripropynyl borate did not react with hydrogen chloride at 20°, but triallyl borate after 14 hours at 120° afforded allyl chloride, 1 : 2-dichloropropane, presumably formed by addition of hydrogen chloride to the former, and boric acid. Hydrogen bromide reacted with triallyl borate at 20° by dealkylation and addition, as was made evident by isolation of allyl bromide and tri-3-bromopropyl borate. The corresponding iodo-products were obtained when hydrogen iodide was employed, but

$$(CH_2{:}CH{\cdot}CH_2{\cdot}O)_3B + 3HHal \begin{cases} \nearrow\ 3CH_2{:}CH{\cdot}CH_2Hal + B(OH)_3 \\ \searrow\ (Hal{\cdot}CH_2{\cdot}CH_2{\cdot}CH_2{\cdot}O)_3B \end{cases}$$

the tri-3-iodopropyl borate could not be adequately purified. The anti-Markownikoff addition is probably explained by an electromeric effect in the allylic double bond of the borate in the direction of the boron atom, encouraged by the electron-attracting power of that atom.

Although allyl alcohol instantly reacted with 0·3N-bromine in carbon tetrachloride, no addition was observed with the orthoborate under these conditions. This is not the case [9] with many other allyl esters (*e.g.*, acetate and phthalate). In substantially more concentrated solutions a near quantitative yield of tri-2 : 3-dibromopropyl borate was obtained (see also ref. 10).

Both diallyl and dimethallyl ether readily reacted with boron trichloride at low temperature by fission. At −80°, a white solid was formed in each case, probably the ether–trichloride complex, but this was too unstable to be characterised.

$$ROR + BCl_3 \longrightarrow [1:1\ Complex] \longrightarrow RCl + RO{\cdot}BCl_2 \longrightarrow RCl + [BOCl]$$

$$3ROR + 2BCl_3 \longrightarrow 6RCl + B_2O_3$$

The reaction of boron trichloride with the mixed allyl methallyl ether was investigated, because it had previously been shown [1c] that the more electron-releasing of the alkyl groups in a mixed dialkyl ether gave the chloroalkane, whilst the dichloroboronite resulted from the other group. As the alkenyl dichloroboronites are not stable (see above), the trichloride and ether were mixed in the proportions 1 : 2, in order that the orthoborate, which was the known product of chloroboronate decomposition, could be identified. The isolation of triallyl borate indicates that methallyl–oxygen fission had occurred. This suggests that the methallyl group is the more electron-releasing, probably owing to the additional $+I$ effect of the methyl group.

[8] Colclough, Gerrard, and Lappert, *J.*, 1955, 907.
[9] Boyd and Roach, *Analyt. Chem.*, 1947, **19**, 158.
[10] Councler, *Ber.*, 1877, **10**, 1655.

Experimental

Preparations and Techniques.—Dimethallyl ether and allyl methallyl ether were prepared by Tamele, Ott, Marple, and Hearne's method.[11] Hydrogen chloride was generated from dry ammonium chloride and concentrated sulphuric acid, hydrogen bromide by Gerrard's method,[12] and hydrogen iodide from phosphorus, iodine, and water. The hydrogen halides were dried by passage through phosphoric oxide. Boron trichloride was distilled before use. Chlorine attached to boron, and boron, were estimated by hydrolysis and acidimetric titration, and halogen in alkenyl halides by the Volhard method after hydrolysis by ethanolic sodium hydroxide in sealed tubes. Pyridine in complexes (which were all washed with pentane, then dried at reduced pressure) was estimated by steam-distillation from sodium hydroxide solution and titration of the distillate with sulphuric acid (bromophenol-blue).

Preparation of Orthoborates.—Trimethallyl borate (93%), b. p. 118°/19 mm., m. p. 29·5—30° (Found: B, 4·84. Calc. for $C_{12}H_{21}O_3B$: B, 4·83%), was obtained by dropwise addition of boron trichloride (1 mol.) in *n*-pentane (6 mols.) to the alcohol (3 mols.) at −80°, followed by immediate removal of volatile matter at 15°/15 mm. When pyridine (3 mols.) was mixed with the alcohol the yield of borate was 58%, owing to formation of the pyridine–boron trichloride compound. *Triprop-2-yn-1-yl borate* (94%), b. p. 99°/12 mm., n_D^{20} 1·4540, d_4^{16} 1·040 (Found: C, 61·3; H, 5·2; B, 6·17. $C_9H_9O_3B$ requires C, 61·4; H, 5·1; B, 6·15%), was likewise obtained in absence of pyridine. Triallyl borate (85%), b. p. 76°/15 mm., n_D^{21} 1·4276, d_4^{20} 0·926 (Found: B, 5·9. Calc. for $C_9H_{15}O_3B$: B, 5·9%), was likewise obtained, except that methylene dichloride (about 2 mols.) was the solvent. The yield of borate was 58% when the order of mixing was reversed. When allyl alcohol (1 mol.) was added dropwise to boron trichloride (1 mol.) at −80°, the mixture being allowed to remain at 20° for 2 hr., allyl chloride (85%), b. p. 45° (Found: Cl, 46·2. Calc. for C_3H_5Cl: Cl, 46·4%), was removable at 15°/15 mm. and there was a residue containing boron equivalent to boron trioxide (1·81 g., 100%).

Interaction of the Orthoborates and Boron Trichloride.—The reactants were mixed at −80° in the proportions appropriate to the formation of the dichloroboronite or the chloroboronate. Specimens in sealed tubes were stored at 20° and at stated times (Table) the loss of easily hydrolysable chlorine was determined and interpreted as extent (%) of decomposition of the chloro-ester according to the reactions: $B(OR)_3 + 2BCl_3 \longrightarrow 3RO{\cdot}BCl_2 \longrightarrow 3RCl + [3BOCl \longrightarrow B_2O_3 + BCl_3]$; $2B(OR)_3 + BCl_3 \longrightarrow 3(RO)_2BCl \longrightarrow 3RCl + [3RO{\cdot}BO \longrightarrow B(OR)_3 + B_2O_3]$.

System * no.	$B(OR)_3$ (mol.)	BCl_3 (mol.)	R	Decomposition (%), time in hr. 0·25	0·5	1	3	20	27	44	50
1	1	2	C_3H_5	94·3	—	97·1	—	—	—	—	—
2	1	2	C_4H_7	90·9	91·8	—	—	—	—	—	—
3	2	1	C_3H_5	—	20	—	—	37	43	47·5	51
4	2	1	C_4H_7	—	5	—	11	—	31	35·5	36

* Each system equivalent to 3 mols. of chloro-ester.

Freshly mixed reactants no. 3, after being heated for 4 hr. at 100° under reflux, afforded allyl chloride (77%) (Found: Cl, 46·0%), triallyl borate (77·7%), b. p. 82—84°/20 mm. (Found: B, 6·01%), and boron trioxide. Similarly system no. 2 (120° for 15 min.) gave methallyl chloride (78%), b. p. 71—72°, n_D^{20} 1·4284 (Found: Cl, 38·5. Calc. for C_4H_7Cl: Cl, 39·2%), boron trichloride (82%), and boron trioxide (91%). System no. 1, prepared in *n*-pentane (6 mols.) at −80°, immediately afforded, on addition of pyridine (3 mols.), the 1 : 1 *pyridine–allyl dichloroboronite complex* (94%), m. p. 61° (Found: Cl, 30·2; B, 5·1; C_5H_5N, 37·5. $C_8H_{10}ONCl_2B$ requires Cl, 32·5; B, 4·95; C_5H_5N, 36·3%), as a white solid (sparingly soluble in water), which (3·08 g.) at 150° (5·5 hr.) gave allyl chloride (0·53 g.) and a solid (2·45 g.), insoluble in *n*-pentane, comprising the water-reactive pyridine–boron oxychloride complex (Found: Cl, 24·6; B, 6·1; C_5H_5N, 54·7. Calc. for C_5H_5ONClB: Cl, 25·1; B, 7·65; C_5H_5N, 56·0%), and an insoluble substance (Found: Cl, 25·2; B, 9·0; C_5H_5N, 52·3%). System no. 1 in *n*-pentane, added to pyridine (6 mols. in *n*-pentane 10 mols.), gave the *dipyridine–allyl dichloroboronite complex* (95% after being at 15°/0·4 mm.) (Found: Cl, 22·4; B, 3·8; C_5H_5N, 50·8. $C_{13}H_{15}ON_2Cl_2B$ requires Cl, 23·9; B, 3·6; C_5H_5N, 53·2%) as an easily hydrolysable white solid.

[11] Tamele, Ott, Marple, and Hearne, *Ind. Eng. Chem.*, 1941, **33**, 115.
[12] Gerrard, *Research*, 1954, **7**, S 20.

To system no. 3, prepared in methylene dichloride (6 mols.) at −80°, pyridine (3 mols. in the same solvent, 3 mols.) was added at −80°. Volatile matter was removed at 15°/15 mm., and the residue comprised the pyridine–allyl dichloroboronite 1 : 1 complex (100%) (Found : Cl, 29·8; B, 4·81; C_5H_5N, 36·2%), insoluble in *n*-pentane; triallyl borate (91%) and pyridine (69%) were extracted by *n*-pentane. When system no. 3 in *n*-pentane was added to pyridine (6 mols.) in *n*-pentane, the *dipyridine–diallyl chloroboronate compound* (80%) (Found : Cl, 11·9; C_5H_5N, 50·6. $C_{16}H_{20}O_2N_2ClB$ requires Cl, 12·0; C_5H_5N, 49·7%) was obtained as a white solid.

The system no. 2 prepared at −39°, added to pyridine (6 mols.) at −80°, afforded the *dipyridine–methallyl dichloroboronite compound* (80%, after being at 15°/15 mm.) (Found : Cl, 22·4; C_5H_5N, 49·5. $C_{14}H_{17}ON_2Cl_2B$ requires Cl, 22·8; C_5H_5N, 50·8%), a readily hydrolysable white solid. To system no. 4, prepared in methylene dichloride, pyridine (3 mols.) was added at −80°. Volatile matter was removed at 15°/10 mm., leaving the solid *pyridine–dimethallyl chloroboronate compound* (95%) (Found : Cl, 12·1; B, 3·97; C_5H_5N, 29·4. $C_{15}H_{19}O_2NClB$ requires Cl, 13·3; B, 4·04; C_5H_5N, 29·6%), which after being heated at 120° (4 hr., reflux), afforded at 15°/0·4 mm. a liquid (0·49 g.), a mixture of trimethallyl borate (4·43 g., 93%), m. p. 27·5° (Found : B, 4·88%) (extracted by *n*-pentane), and a residue of crude dipyridine–dichloroboronite complex (6·1 g.) (Found : Cl, 25·0; B, 4·1; C_5H_5N, 45·1%).

Certain Properties of Triallyl Borate.—The borate (1·99 g.) was recovered after hydrogen chloride had been passed through it for 3·5 hr. at 15°, but at 120° (14 hr.) allyl chloride (1·08 g.), dichloropropane (0·73 g.), b. p. 93·5°, n_D^{15} 1·4310, triallyl borate (0·20 g.), b. p. 59°/13 mm., and boric acid (0·48 g.) were obtained. After hydrogen bromide had been passed (8 hr.) into the borate (4·78 g.) at 20°, matter volatile at 15°/15 mm. was condensed (3·87 g.) and separated into allyl bromide (3·61 g.), b. p. 66° (Found : Br, 65·8. Calc. for C_3H_5Br : Br, 66·1%), and dibromopropane (0·18 g.), b. p. 60°/16 mm. The less volatile residue (6·96 g.) was separated by methylene dichloride into boric acid (0·73 g.) and *tri-3-bromopropyl borate* (6·15 g.), b. p. 112°/0·01 mm. (Found : Br, 55·4; B, 2·53. $C_9H_{18}O_3Br_3B$ requires Br, 56·5; B, 2·55%), which on hydrolysis afforded 3-bromopropan-1-ol, b. p. 78°/17 mm., n_D^{17} 1·4863 (Found : Br, 57·0. Calc. for C_3H_7OBr : Br, 57·5%). Hydrogen iodide was passed into the borate (3·57 g.) (0·67 hr.) at 20°, whereupon allyl iodide (2·5 g.), n_D^{18} 1·5094 (Found : I, 73·8. Calc. for C_3H_5I : I, 75·6%), was obtained as a condensate at 15 mm., and the residue (4·48 g.) comprised boric acid (0·18 g.) (separated by methylene dichloride), triallyl borate (1·32 g.), b. p. 80°/18 mm. (Found : B, 5·78%), and a final residue of tri(iodopropyl) borate (2·1 g.) (Found : I, 65·8. Calc. for $C_9H_{18}O_3I_3B$: I, 67·4%). On hydrolysis and extraction with ether, the iodo-alcohol could not be isolated owing to constant liberation of iodine.

Triallyl borate (2·56 g., 1 mol.) did not react with bromine (0·3N) in carbon tetrachloride, but did so at 5° with bromine (6·75 g., 3 mols.) in the same solvent (25 c.c.). After removal of volatile matter at 15°/10 mm., tri-2 : 3-dibromopropyl borate (8·83 g., 95%), m. p. −16° (Found : Br, 71·3; B, 1·64. Calc. for $C_9H_{15}O_3Br_6B$: Br, 72·5; B, 1·64%), was obtained as an undistillable, viscous, orange liquid, readily hydrolysed to 2 : 3-dibromopropanol, b. p. 109°/19 mm., n_D^{20} 1·5557, d_4^{18} 2·138.

Interaction of Ethers and Boron Trichloride.—(a) *Diallyl ether.* The ether (5·02 g., 3 mols.) was added (25 min.) to boron trichloride (4·00 g., 2 mols.) at −80°. A white solid was formed, but disappeared on warming. Allyl chloride (6·6 g., 84%), b. p. 46° (Found : Cl, 46·2%), was obtained as a condensate (15 mm.), after prior heating to ensure complete decomposition of chloroboronate, and there was a residue (1·90 g.) containing boron trioxide (1·10 g., 93%).

Addition of diallyl ether (5·17 g., 1 mol.) in *n*-pentane (20 c.c.) to boron trichloride (6·18 g., 1 mol.) in *n*-pentane (20 c.c.) at −80° gave a white precipitate. At −20° this began to decompose exothermally, and therefore was immediately cooled. Addition of pyridine (4·17 g., 1 mol.) at −80° gave pyridine–boron trichloride (2·40 g.), m. p. 109°, insoluble in *n*-pentane and in cold water.

(b) *Dimethallyl ether.* The ether (7·60 g., 3 mols.) was slowly (25 min.) added to the trichloride (4·71 g., 2 mols.) at −80°. Similar observations were made as in (a) and a similar method yielded methallyl chloride (8·06 g., 74%), b. p. 72°, n_D^{20} 1·4279 (Found : Cl, 38·9%), and boron trioxide (1·32 g., 95%).

(c) *Allyl methallyl ether.* The ether (5·28 g., 2 mols.) was added (15 min.) to the trichloride (2·76 g., 1 mol.) in *n*-pentane (15 c.c.) at −80°. Volatile matter was removed (15°/10 mm.) and a brown viscous liquid remained. This was distilled to give triallyl borate (1·36 g., 96%), b. p. 58°—65°/9 mm. (Found : B, 5·8%), and a residue of boron trioxide (0·73 g., 100%).

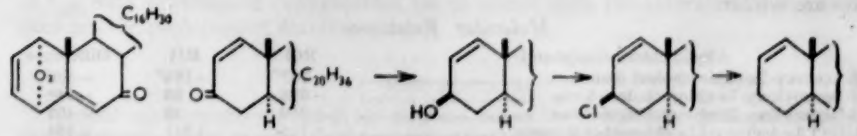
The Northern Polytechnic, Holloway, London, N.7. [*Received, March 28th*, 1956.]

638. *Preparation of 1-Oxygenated Steroids. The Reaction of Cholest-1-en-3β-ol with Thionyl Chloride.*

By H. B. Henbest and R. A. L. Wilson.

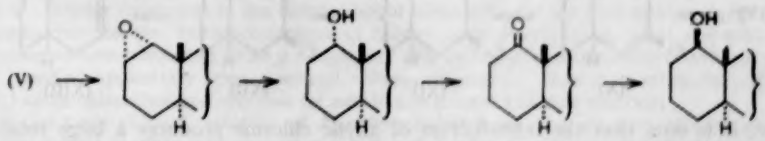
An unambiguous route to cholestan-1α-ol and related compounds is described. A key step in the synthesis involves the conversion of cholest-1-en-3β-ol into 3β-chlorocholest-1-ene by thionyl chloride. Rearrangement does not occur in this replacement, in contrast to the observations of Goering, Nevitt, and Silversmith [1] with monocyclic *cyclo*hexenols.

For the synthesis of 1-oxygenated steroids, unknown when this work began, two routes were considered. First, the photo-catalysed addition of oxygen to cholesta-1 : 3 : 5-trien-7-one was studied. Although the required 1 : 4-epidioxide (I) was obtained from this reaction,[2] the low yield (15%) rendered further development unattractive. The second route required a method for converting cholest-1-en-3-one (II) into cholest-1-ene (V), whereby isomerisation of the 1 : 2-double bond to the more stable 2 : 3-position could be avoided.[3,4,5] Reduction of the ketone (II) by lithium aluminium hydride gave the 3β-alcohol (III) in high yield.[5,6] In contrast to the observations of Plattner and his co-workers,[5] it was found that a crystalline chloro-compound was readily obtained from the reaction of this alcohol with thionyl chloride. Further details concerning this reaction



(I) (II) (III) (IV) (V)

and the proof of structure of the chloro-compound as (IV) are given below. For reduction of the chloro-compound without double-bond migration, lithium aluminium hydride proved to be the most effective reagent, a good yield of cholest-1-ene (V) being isolated *via* its dibromide (the infrared spectra of cholest-1-ene and related compounds have been discussed previously [3]). The ultraviolet absorption spectrum of the crude hydrocarbon from the reduction indicated that the main impurity was, not cholest-2-ene, but the as yet undescribed cholesta-1 : 3-diene, part of the hydride apparently acting as a base. Other methods of reduction tended to give more cholest-2-ene than the desired-1-ene (V); for instance, catalytic hydrogenation with palladium–strontium carbonate afforded a good yield of olefin shown by infrared analysis [3] to consist of the Δ^2-compound (75%) and the Δ^1-compound (25%).



(VI) (VII) (VIII) (IX)

Oxidation of cholest-1-ene (V) by monoperphthalic acid gave a single epoxide, assigned an α-configuration (VI) by analogy with the behaviour of cholest-2- and -3-ene which

[1] Goering, Nevitt, and Silversmith, *J. Amer. Chem. Soc.*, 1955, **77**, 4042.
[2] Henbest and Wilson, *Chem. and Ind.*, 1956, 86.
[3] Henbest, Meakins, and Wood, *J.*, 1954, 800.
[4] Turner, XIVth Internat. Congr. Pure and Appl. Chem., 1955, Abs., paper 594.
[5] Plattner, Fürst, and Els, *Helv. Chim. Acta*, 1954, **37**, 1399.
[6] Bergmann, Kita, and Giancola, *J. Amer. Chem. Soc.*, 1954, **76**, 4974.

both yield α-epoxides exclusively [7,8] and because reduction by lithium aluminium hydride gave the 1α-alcohol (VII) (the β-epoxide would have given the known 2β-alcohol), oxidised to the 1-ketone (VIII), which readily formed a 2 : 4-dinitrophenylhydrazone. Sodium–ethanol reduction of the ketone gave the equatorial 1β-alcohol (IX) in 65% yield, the remainder being the 1α-hydroxy-compound.

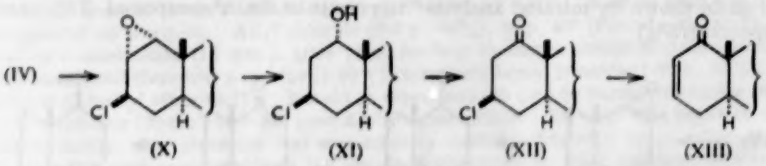
The direction of reduction of cyclic ketones by lithium aluminium hydride seems to depend on steric factors which are difficult to evaluate with precision. Previous work in the steroid series indicates that there is a general tendency for β-alcohols to be formed by reduction from the α-side (less hindered by the bulky angular methyl groups). Thus it was somewhat surprising to find that the ratio of 1α- to 1β-alcohol produced by hydride reduction of the 1-ketone was approximately 2 : 1, especially in view of the proximity of the 10β-methyl group. The present difficulty of predicting the more likely product from addition reactions of polycyclic ketones is well shown by the observations of Heusser, Wahba, and Winternitz [9] that reaction of methylmagnesium bromide with a 17*a*-oxo-homosteroid, containing a six-membered ring D, gave a 17β-methyl compound (the same direction incidentally as the major route taken by hydride reduction of the 1-ketone), whereas a similar Grignard reaction with a 17-oxosteroid containing a five-membered ring D yielded a 17α-methyl compound as the main product.

As this work was nearing completion, two publications [5,10] appeared describing syntheses of 1-oxygenated steroids. The simplicity of the present method, proceeding through four crystalline intermediates (from II), seems advantageous; the overall yields of the three routes are similar.

Molecular Rotations

Allylic chloro-compound	RCl	RH	Difference
3β-Acetoxy-7α-chlorocholest-5-ene	−762°	−166°	−596°
3β-Benzoyloxy-7α-chlorocholest-5-ene	−623	− 83	−540
3β-Benzoyloxy-7β-chlorocholest-5-ene	+319	− 83	+402
Methyl 3α-acetoxy-12α-chlorochol-9-enate	+715	+241	+464
3β-Chlorocholest-1-ene (IV)	+404	+ 48	+356

As mentioned above, reaction of cholest-1-en-3β-ol with thionyl chloride affords a crystalline chloro-compound (75% yield), reduced to cholest-1-ene by lithium aluminium hydride. However, the latter reaction does not provide unambiguous proof that chlorine is situated at $C_{(3)}$ for the Δ^1-olefin could have been formed from an isomeric 1-chloro-Δ^2-compound by a S_N2' reaction. The chloro-compound thus corresponds to one of the four possible structures depending upon whether inversion and/or rearrangement occurs during the thionyl chloride reaction. Two of the structures could be ruled out by molecular-rotation evidence. If the rotations of the steroid allylic chlorides of known structure (Table) are compared with the values given by the corresponding compounds lacking



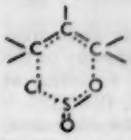
(X) (XI) (XII) (XIII)

chlorine, it is seen that the introduction of allylic chlorine produces a large rotational change in the direction predicted by Mills's rule [11] concerning cyclic allylic systems. Comparison of the rotation of the chloro-compound under discussion with those of cholest-1- and -2-ene shows (by the direction of rotational shift) that the structure is either 3β-chlorocholest-1-ene (IV) or 1α-chlorocholest-2-ene, the latter being somewhat less likely as the magnitude of the shift (+150°) would then be smaller than expected.

[7] Fürst and Plattner, *Helv. Chim. Acta*, 1949, **32**, 275.
[8] Fürst and Scotoni, *ibid.*, 1953, **36**, 1332.
[9] Heusser, Wahba, and Winternitz, *ibid.*, 1954, **37**, 1052.
[10] Striebel and Tamm, *ibid.*, 1954, **37**, 1094.
[11] Mills, *J.*, 1952, 4976.

In order to distinguish between these two possibilities, the chloro-compound was converted into the epoxide (X) with perbenzoic acid, and this was transformed in turn into the axial alcohol (XI), the chloro-ketone (XII), and the known unsaturated ketone [10] (XIII). The alternative 1-chloro-Δ^2-structure would have yielded the Δ^1-3-ketone by this sequence of reactions.

Although no attempt was made to investigate further the thionyl chloride reaction leading to the formation of the chloride (IV), the observation that the hydroxyl group is largely replaced without allylic rearrangement may be contrasted with the results of Goering, Nevitt, and Silversmith [1] with a monocyclic allylic *cyclo*hexenol system. In their elegant studies with these compounds [bearing the same degree of substitution on the allylic system as (III)], they showed that thionyl chloride in ether gave rearranged chloride with a high degree of specificity, and a cyclic transition state of the type shown was suggested following the earlier proposals of Young and his co-workers.[12] However, with the steroid compounds the unrearranged chloride (IV) was the major product from the reaction in ether, dioxan, or benzene. The most probable explanation of this difference appears to be that in the monocyclic series the intermediate chlorosulphite group can assume a quasiaxial configuration from which the transition state leading to rearrangement can develop readily, whereas with the steroid compound the quasiequatorial configuration of the chlorosulphite group attached to the relatively rigid ring system causes the chlorine to be too far removed from $C_{(1)}$ for a similar transition state to be elaborated. Replacement at $C_{(3)}$ with retention of configuration (as of course with the saturated 3β-alcohol) thus becomes the predominant reaction.



Experimental

General experimental directions are as given before.[13] The infrared absorption spectra of the compounds prepared were consistent with the structures assigned.

Cholest-1-*en*-3β-*ol* (III). A solution of cholest-1-en-3-one (2·4 g.) in ether (150 c.c.) was cooled to −40° and lithium aluminium hydride (0·24 g.) in ether (30 c.c.) was added with stirring. The solution was allowed to warm to 20°, and after the addition of ethyl acetate and dilute sulphuric acid the steroid was isolated with ether. Crystallisation from methanol afforded the 3β-alcohol (1·7 g.) as needles, m. p. 130—132°, $[\alpha]_D$ +55°. The acetate had m. p. 84—86°, $[\alpha]_D$ +58°; the benzoate had m. p. 141—142°, $[\alpha]_D$ +95°.

3β-*Chlorocholest*-1-*ene* (IV).—Thionyl chloride (1·5 c.c.; purified by successive distillation from quinoline and linseed oil) was added to a solution of the foregoing alcohol (1·5 g.) in benzene (50 c.c.). The solution was kept at 20° for 1 hr., then the steroid was isolated in the usual way. Crystallisation from acetone afforded the *chloro-compound* (0·80 g.) as needles, m. p. 95—101°, $[\alpha]_D$ +100° (Found: C, 80·2; H, 10·9; Cl, 8·65. $C_{27}H_{45}Cl$ requires C, 80·1; H, 11·1; Cl, 8·8%). Similar results were obtained with ether or dioxan as solvent.

Treatment of the pure chloro-compound with aniline at 20° gave a quantitative yield of an anilino-steroid, m. p. 142—144°, the structure of which will be discussed in a separate communication. Similar treatment of the chloro-steroid obtained from the first mother-liquor from the crystallisation of the 3β-chloro-compound (above experiment) gave, after chromatography, the same anilino-compound (0·46 g.) together with an isomeric anilino-derivative, m. p. 163—166°, derived apparently from a second chloro-compound. Thus it is estimated that 1·2 g. (75%) of 3β-chlorocholest-1-ene was formed in the thionyl chloride reaction.

Cholest-1-*ene* (V).—A solution of 3β-chlorocholest-1-ene (1·4 g.) and lithium aluminium hydride (0·7 g.) in ether (120 c.c.) was heated under reflux for 16 hr. Ethyl acetate and dilute sulphuric acid were added, the steroid was isolated with light petroleum, and the solution filtered through alumina (50 g.). Crystallisation from acetone gave crude cholest-1-ene (1·0 g.) as needles, m. p. 66—69°, showing an ultraviolet absorption maximum at 2630 Å (ε 1080; the absorption being assumed due to cholesta-1 : 3-diene, the intensity value probably indicates that about 20% of the diene is present). The crude Δ^1-compound was dissolved in ether (50 c.c.) and treated with M-bromine in acetic acid (2·25 c.c.). After 10 min. the solvent was removed under reduced pressure, and the product crystallised from ethyl methyl ketone, to

[12] Young, Brandon, and Caserio, *Science*, 1953, **117**, 473.
[13] Bladon, Henbest, Jones, Wood, Eaton, and Wagland, *J.*, 1953, 2916.

give 1α : 2β-*dibromocholestane* (1·0 g.) as needles, m. p. 134—136°, $[\alpha]_D$ +32° (Found : C, 60·75; H, 8·7. $C_{27}H_{46}Br_2$ requires C, 61·1; H, 8·75%).

A solution of the dibromide (3·4 g.) in acetic acid (175 c.c.) was heated to boiling and zinc dust (16 g.) was then added in portions. The solution was heated under reflux for 1·5 hr., the solvent removed under reduced pressure, and the residue extracted with light petroleum. These extracts were filtered through alumina and evaporated, and the product was crystallised from acetone to afford *cholest-1-ene* (1·8 g.) as needles, m. p. 69—70°, $[\alpha]_D$ +13° (Found : C, 87·25; H, 12·5. $C_{27}H_{46}$ requires C, 87·5; H, 12·5%).

1α : 2α-*Epoxycholestane* (VI).—Solutions of cholest-1-ene (0·5 g.) in ether (20 c.c.) and 2·5N-monoperphthalic acid in ether (3 c.c.) were mixed and kept at 20° for 3 days. Isolation of the product in the usual way followed by crystallisation from acetone gave the *epoxide* (0·37 g.) as prisms, m. p. 86—88°, $[\alpha]_D$ +10° (Found : C, 84·1; H, 12·2. $C_{27}H_{46}O$ requires C, 83·9; H, 12·0%).

Cholestan-1α-ol (VII).—A solution of the 1α : 2α-epoxide (1·15 g.) and lithium aluminium hydride (0·7 g.) in ether (300 c.c.) was heated under reflux for 2·5 hr. Chromatography of the product gave cholestan-1α-ol (0·85 g.), prisms (from methanol), m. p. 93—95°, remelting at 103—105°, $[\alpha]_D$ +35° (Found : C, 83·6; H, 12·6. Calc. for $C_{27}H_{48}O$: C, 83·4; H, 12·5%).

Acetylation with acetic anhydride and pyridine for 10 days at 20° yielded 1α-*acetoxycholestane*, needles (from methanol), m. p. 73—75°, $[\alpha]_D$ +43° (Found : C, 81·0; H, 11·7. $C_{29}H_{50}O_2$ requires C, 80·9; H, 11·7%). This compound was prepared but not obtained crystalline by Striebel and Tamm.[10]

Oxidation of the 1α-alcohol (0·9 g.) by the chromic acid–acetone technique,[14] followed by crystallisation of the product from methanol, afforded cholestan-1-one (0·73 g.) as prisms, m. p. 87—89°, $[\alpha]_D$ +114°. Its 2 : 4-*dinitrophenylhydrazone* crystallised from dioxan–methanol as yellow needles, m. p. 184—187° (Found : N, 9·6. $C_{33}H_{50}O_4N_4$ requires N, 9·9%).

Reduction of Cholestan-1-one.—A solution of lithium aluminium hydride (0·15 g.) and the ketone (0·25 g.) in ether (100 c.c.) was heated under reflux for 2 hr. The product was chromatographed on alumina (25 g.). Elution with light petroleum–benzene (1 : 3; 200 c.c.) gave cholestan-1α-ol (0·13 g.), m. p. and mixed m. p. 91—94°, remelting at 103—105°. Further elution with the same solvent afforded cholestan-1β-ol (70 mg.), which crystallised from methanol as needles, m. p. 82—84°, $[\alpha]_D$ +22·5°.

Sodium–ethanol reduction of the ketone (0·18 g.) followed by chromatography yielded the 1α-alcohol (60 mg.) and the 1β-alcohol (0·11 g.).

3β-*Chloro*-1α : 2α-*epoxycholestane* (X).—A 0·1M-solution of perbenzoic acid in benzene (60 c.c.) was added to a solution of 3β-chlorocholest-1-ene (0·5 g.) in benzene (30 c.c.) at 5°. The solution was kept at this temperature for 2 days, then the steroid was isolated in the usual way. Crystallisation from acetone yielded the α-*epoxide* (0·32 g.) as needles, m. p. 129—131°, $[\alpha]_D$ +27·5° (Found : C, 77·3; H, 10·9. $C_{27}H_{45}OCl$ requires C, 77·0; H, 10·8%).

3β-*Chlorocholestan-1α-ol* (XI).—A solution of the chloro-epoxide (0·2 g.) and lithium aluminium hydride (0·5 g.) in ether (50 c.c.) was heated under reflux for 3 hr. Crystallisation of the product from acetone gave the *chloro-alcohol* (0·12 g.) as needles, m. p. 119—123°, $[\alpha]_D$ +34° (Found : C, 76·4; H, 11·3. $C_{27}H_{47}OCl$ requires C, 76·7; H, 11·2%).

Cholest-2-en-1-one (XIII).—3β-Chlorocholestan-1α-ol (0·16 g.) was oxidised by the chromic acid–acetone technique.[14] The product, dissolved in benzene, was filtered through alumina (10 g.) to yield cholest-2-en-1-one (0·1 g.), which on crystallisation from methanol–acetic acid (1 : 1) had m. p. 56—57°, $[\alpha]_D$ +121°; ultraviolet absorption (in EtOH), $\lambda_{max.}$ 2240 and 3300 Å (ε 8100 and 54 respectively). Striebel and Tamm [10] record m. p. 56—57°, $[\alpha]_D$ +120°; ultraviolet absorption, $\lambda_{max.}$ 2220 and 3400 Å (ε 7940 and 52 respectively).

The authors thank Professor E. R. H. Jones, F.R.S., for his interest in this work, Dr. G. D. Meakins for the infrared spectra, Mr. E. S. Morton for microanalyses, and the Department of Scientific and Industrial Research for a Maintenance Grant (to R. A. L. W.).

The University, Manchester, 13. [*Received, April 3rd*, 1956.]

[14] Bladon, Fabian, Henbest, Koch, and Wood, *J.*, 1951, 2402.

639. *A Search for New Trypanocides. Part II.** 4-*Amino*-6-*dialkylaminoquinaldines.*

By H. Bader.

Some 6-*NN*-disubstituted derivatives of 4 : 6-diaminoquinaldine are described, of which only 4-amino-6-piperidinoquinaldine had a curative effect on *Trypanosoma rhodesiense* infections in mice.

The 4 : 6-diaminoquinaldine structure occurs in several chemotherapeutic drugs, such as Surfen-C, Antrycide, αω-di-(4-amino-6-quinaldyl)aminoalkanes,[1] and diamides derived from 4 : 6-diaminoquinaldine and various dicarboxylic acids.[2] Having discovered [3] that 4-amino-6-piperidinoquinaldine possessed activity against *Trypanosoma rhodesiense*, we decided to prepare further compounds of this type, *e.g.*, 4-amino-6-dialkylaminoquinaldines.

The first attempt was by direct alkylation of 4 : 6-diaminoquinaldine with alkyl halides in presence of alkali in ethanol or aqueous ethanol. Whereas the 6-amino-group reacts as a true amino-group, the other resembles the amino-group in 4-aminopyridine and behaves as in the tautomeric 4-quinolone imide. In view of this, dialkylation of the 6-amino-group was attempted, although it was realised that some of the 1-alkyl-4-quinolone imide might also be formed. These alkylations were unsuccessful, but in one case a small yield of 4-amino-6-diethylaminoquinaldine ethiodide was obtained.

A possible alternative route seemed to lie in the reaction between the lithium derivatives of dialkylamines with 4-amino-6-bromoquinaldine, a reaction which is successful with aromatic bromides.[4] However, reaction of 4-amino-6-bromoquinaldine (prepared by fusing 6-bromo-4-methoxyquinaldine with ammonium acetate) with lithium diethylamide in ether gave only tars. The required dialkylamino-derivatives were finally obtained from the corresponding *p*-dialkylaminoanilines by the Conrad–Limpach reaction, and conversion of the resulting 6-dialkylamino-4-hydroxyquinaldines successively into the 4-chloro- and 4-amino-analogues.

4-Amino-6-pyrrolidino- and 4-amino-6-piperidino-quinaldine were prepared by direct reaction of the appropriate polymethylene dibromide with 4 : 6-diaminoquinaldine in ethanol at 160—180°.

All the compounds formed colourless dihydrochlorides, but often (mainly with the 4-chloro-intermediates) the salts tended to lose hydrogen chloride on exposure to air or when heated.

None of these compounds was active against *T. congolense* infections in mice, and only 4-amino-6-piperidinoquinaldine had a curative effect on *T. rhodesiense* infections.

Experimental

N-Methyl-N-n-propylaniline.—Recorded preparations [5] were improved as follows. *N*-Methylaniline (80 g.) was heated with *n*-propyl bromide (110 g.) at 95° for 22 hr. Treating the cold, solidified mixture with excess of 50% aqueous sodium hydroxide gave an oil, which after isolation by means of ether, yielded *N*-methyl-*N*-*n*-propylaniline (99 g.), b. p. 116·5—119°/12 mm., $n_D^{19·5}$ 1·5403. The picrate crystallised from ethanol in yellow prisms, m. p. 109·5° (lit.,[6] 106—107°, 110·5°).

p-Amino-N-methyl-N-n-propylaniline.—The crude nitroso-derivative prepared by Stoermer and von Lepel's method [5] from *N*-methyl-*N*-*n*-propylaniline (89 g.), concentrated hydrochloric acid (116 c.c.), and sodium nitrite (46 g.), was added with stirring and cooling to a solution of crystalline stannous chloride (210 g.) in concentrated hydrochloric acid (240 c.c.). The mixture was then refluxed for 30 min. and left to cool; then the base was liberated by 50% aqueous

* Part I, *J.*, 1956, 337.

[1] Jensch, *Z. angew. Chem.*, 1937, **50**, 891; U.S.P. 2,050,971.
[2] Pratt and Archer, *J. Amer. Chem. Soc.*, 1948, **70**, 4065; Goble, *J. Pharmacol.*, 1950, **98**, 49.
[3] Stone, personal communication.
[4] Cf. Hornung and Bergstrom, *J. Amer. Chem. Soc.*, 1945, **67**, 2110; Gilman *et al.*, *ibid.*, 1945, **67**, 2106; 1946, **68**, 143.
[5] Claus and Hirzel, *Ber.*, 1886, **19**, 2787; Stoermer and von Lepel, *Ber.*, 1896, **29**, 2112.
[6] Singh, *J.*, 1916, **109**, 791; Wagner, *J. Amer. Chem. Soc.*, 1933, **55**, 724.

sodium hydroxide; distillation gave p-*amino*-N-*methyl*-N-n-*propylaniline* (66 g.), b. p. 154—155°/17 mm., $n_D^{20.6}$ 1·5670 (Found: N, 16·9. $C_{10}H_{16}N_2$ requires N, 17·05%).

NN-*Di*-n-*butylaniline*.—Conditions, mentioned by Reilly and Hickinbottom,[7] were supplemented as follows: aniline (36·1 c.c., 0·4 mol.) and *n*-butyl bromide (43·2 c.c., 0·4 mol.) were refluxed for 40 min. The oil obtained on addition of aqueous sodium hydroxide gave mono-*n*-butylaniline (36·5 g.), b. p. 253—259°/760 mm., n_D^{22} 1·526. This amine (121 g., 0·8 mol.) and *n*-butyl bromide (130 c.c., 1·2 mol.) were refluxed, in presence of a trace of iodine, for 24 hr. Basification of the reaction mixture afforded di-*n*-butylaniline (126 g.), b. p. 270—275°/760 mm., n_D^{20} 1·5195—1·5200.

p-*Amino*-NN-*di*-n-*butylaniline*.—The above tertiary amine (116·6 g.) was converted into *NN*-di-*n*-butyl-*p*-nitrosoaniline hydrochloride (137 g.), m. p. 105—106°, as described by Reilly and Hickinbottom,[7] by using water (550 c.c.), concentrated hydrochloric acid (290 c.c.), and sodium nitrite (39·4 g.). The nitroso-derivative was reduced to the amine, as described above, with stannous chloride (300 g.) in concentrated hydrochloric acid (360 c.c.). The white suspension was not heated, but was stirred at room temperature for 1 hr. Basification and extraction with benzene gave *p*-amino-*NN*-di-*n*-butylaniline (72 g.), b. p. 127—128°/0·15 mm., n_D^{22} 1·5378—1·5382, which quickly darkened in air. The *dihydrochloride* crystallised from ethanol in colourless prisms, m. p. 206—207° (Found: C, 55·6; H, 9·4; N, 9·25. $C_{14}H_{24}N_2,2HCl,0·5H_2O$ requires C, 55·6; H, 9·0; N, 9·25%).

4-*Amino*-6-*piperidinoquinaldine Dihydrochloride*.—4 : 6-Diaminoquinaldine (10·5 g.), 1 : 5-dibromopentane (6 g.), and ethanol (40 c.c.) were heated at 150° for 3 hr. The mixture was filtered, and the filtrate was evaporated *in vacuo*, to give a yellow solid. Treating this with dilute sodium hydroxide gave the oily base, which after being washed with water by decantation, was treated with methanolic hydrochloric acid. This gave a solid (17·3 g.), which crystallised from ethanolic hydrochloric acid as the *dihydrochloride* (9·45 g.), yellow prisms, sinter from 245°, char from 297° (Found: C, 56·7; H, 6·85; N, 13·15; Cl, 22·3. $C_{15}H_{19}N_3,2HCl$ requires C, 57·3; H, 6·75; N, 13·35; Cl, 22·55%).

4-*Amino*-6-*pyrrolidinoquinaldine Dihydrochloride*.—This was prepared similarly from 4 : 6-diaminoquinaldine (10·35 g.), 1 : 4-dibromobutane (6 g.), and ethanol (30 c.c.). The *dihydrochloride* (15·1 g.) crystallised from ethanol in pale yellow prisms, m. p. 215° (decomp.) (Found: C, 52·35; H, 6·95; N, 13·8; Cl, 22·0. $C_{14}H_{17}N_3,2HCl,H_2O$ requires C, 52·85; H, 6·65; N, 13·2; Cl, 22·25%).

6-*Bromo*-4-*methoxyquinaldine*.—6-Bromo-4-hydroxyquinaldine[8] (100 g.), methyl sulphate (72·4 c.c.), and dry toluene (480 c.c.) were refluxed and stirred for 2 hr. The resulting brown solid was filtered off and washed with ether; it was dissolved in hot water (200 c.c.), the solution was filtered, and excess of 50% aqueous sodium hydroxide was added to the hot filtrate. The oil solidified and the solid was washed with water and extracted several times with boiling light petroleum (b. p. 40—60°; 7 l.). The extract gave 6-bromo-4-methoxyquinaldine (85 g.) which crystallised from light petroleum (b. p. 40—60°) in pinkish needles, m. p. 90—92° (Found: N, 5·7; Br, 32·2. $C_{11}H_{10}ONBr$ requires N, 5·5; Br, 31·75%). This compound was first prepared by Mr. S. S. Berg.

4-*Amino*-6-*bromoquinaldine*.—6-Bromo-4-methoxyquinaldine (20 g.) and ammonium acetate (85 g.) were heated with stirring at 135—140° for 10 min.; a clear orange melt was obtained. After further heating for 3 hr. the melt was poured into water (250 c.c.), whence basification with 50% aqueous sodium hydroxide gave 4-*amino*-6-*bromoquinaldine* (16·6 g.), m. p. 167—169° colourless prisms (from water), m. p. 173° (Found: N, 11·6; Br, 33·6. $C_{10}H_9N_2Br$ requires N, 11·8; Br, 33·75%).

6-*Dimethylamino*-4-*hydroxyquinaldine*.—*p*-Dimethylaminoaniline (77 g.), ethyl acetoacetate (67 g.), and concentrated hydrochloric acid (4 drops) were mixed. Reaction soon occurred with elimination of water, and after 2 hr. the resulting solid was powdered and dried *in vacuo*, giving crude *ethyl* 2-(p-*dimethylaminoanilino*)*crotonate* (135 g.), which recrystallised from light petroleum (b. p. 40—60°) (charcoal) as pale orange, prismatic needles, m. p. 69—70° (Found: C, 67·7; H, 8·15; N, 11·3. $C_{14}H_{20}O_2N_2$ requires C, 67·7; H, 8·1; N, 11·3%). This ester (133 g.) was added during 10 min. to boiling and stirred Dowtherm (diphenyl ether–diphenyl) (1 l.); after boiling for a further 15 min. the mixture was left overnight, then the solid (82 g.) was filtered off and washed with light petroleum (b. p. 40—60°) and ether. The 6-*dimethylamino*-4-*hydroxyquinaldine* crystallised from ethanol–ether (1 : 3) in bright yellow prisms, m. p. 320—322° (Found: C, 71·5; H, 7·1; N, 14·15. $C_{12}H_{14}ON_2$ requires C, 71·25; H, 6·95;

[7] Reilly and Hickinbottom, *J.*, 1918, **113**, 101.
[8] Kermack and Weatherhead, *J.*, 1939, 564.

N, 13·85%). The *dihydrochloride* crystallised from ethanol in colourless prisms, m. p. 264—265° (Found: Cl, 25·5. $C_{13}H_{14}ON_2$,2HCl requires Cl, 25·75%).

4-Chloro-6-dimethylaminoquinaldine.—A solution of 6-dimethylamino-4-hydroxyquinaldine (77 g.) in phosphorus oxychloride (385 c.c.) was refluxed for 30 min., and the mixture was cooled, poured on ice, and basified with 50% aqueous sodium hydroxide. The *chloro-compound* (71 g.), which was extracted by ether, crystallised from ether in bright yellow needles, m. p. 91—92° (Found: C, 65·5; H, 6·35; N, 12·9; Cl, 15·7. $C_{13}H_{13}N_2Cl$ requires C, 65·3; H, 5·95; N, 12·7; Cl, 16·05%). The *hydrochloride* formed colourless prisms, which reddened in air, and became orange when dried at 76° *in vacuo*. The latter form, m. p. 256°, was stable (Found: N, 10·4; Cl, 32·4. $2C_{12}H_{13}N_2Cl$,3HCl requires N, 10·15; Cl, 32·2%).

4-Amino-6-dimethylaminoquinaldine.—Ammonia was passed through a refluxing solution of 4-chloro-6-dimethylaminoquinaldine (15 g.) in phenol (75 g.) which was kept at 180—200° (bath-temp.) for 3 hr. Phenol was then removed by distillation with steam; basification of the residue gave a green solid (13·7 g.). Recrystallisation from ethanol (30 c.c.)–ether (175 c.c.)–light petroleum (b. p. 40—60°; 175 c.c.) gave *4-amino-6-dimethylaminoquinaldine* (12·2 g.), green prisms, which after crystallising successively from hot water and from chloroform–light petroleum (b. p. 40—60°) was obtained in pale green prisms, m. p. 201—203° (Found: N, 21·0. $C_{12}H_{15}N_3$ requires N, 20·85%). The *dihydrochloride* (6·1 g. from 5 g. of base) crystallised from ethanol–methanol (1 : 2) in colourless needles, m. p. 245—246° (Found: N, 15·5; Cl, 25·5. $C_{12}H_{15}N_3$,2HCl requires N, 15·35; Cl, 25·8%).

Ethyl β-(p-*diethylamino*- (80%), straw-coloured prisms (from light petroleum), m. p. 65—66° (Found: N, 10·2. $C_{16}H_{24}O_2N_2$ requires N, 10·15%), and *ethyl* β-(*p-N-methyl-N-propylamino-anilino*)*crotonate* (95%), colourless prisms (from light petroleum), m. p. 58·5° (Found: C, 69·45; H, 8·7; N, 10·2. $C_{16}H_{24}O_2N_2$ requires C, 69·55; H, 8·75; N, 10·15%), were similarly prepared. The oily di-n-butylamino-analogue was cyclised without purification.

Other *compounds*, prepared by cyclisation as above, are recorded in the Table.

4-Substituted 6-dialkylaminoquinaldines.

No.	4-Subst.	*N*-Subst.		Deriv.[a]	Yield (%)	M. p.	Solvent[b] for crystn.	Cryst. form
1	OH	Et	Et	—	62	198—199°	EtOH–Et_2O	Needles
				Salt		238	EtOH–HCl	Prisms
2	OH	Me	Pr^n	—	74	186	EtOH–Et_2O	Green prisms
				Salt		208—209	EtOH	Pale yellow prisms
3	OH	Bu^n	Bu^n	—	—	130	C_6H_6–Et_2O	Green prisms
				Salt[c]	95	206		
4	Cl	Et	Et	—	87	34	MeOH–H_2O	Yellow needles
				Salt		216[d]	EtOH	Straw-coloured needles
5	Cl	Me	Pr^n	—	93	56—57	Petrol	Yellow plates
				Salt		218[d]	EtOH	Pale yellow prisms
6	Cl	Bu^n	Bu^n	Salt	40	179[d]	EtOH–HCl	Needles
7	NH_2	Et	Et	—	95	170·5	$CHCl_3$–Petrol	Pale green needles
				Salt	—	222—223	EtOH	Plates
8	NH_2	Me	Pr^n	Salt	63	197—198	EtOH	Prisms
9	NH_2	Bu^n	Bu^n	Salt	50	203—204	EtOH–HCl	Pale yellow plates

		Found (%)					Required (%)			
No.		C	H	N	Cl	Formula	C	H	N	Cl
1	Base	72·8	7·65	11·9	—	$C_{14}H_{16}ON_2$	73·0	7·9	12·15	—
	Salt				23·2					23·4
2	Base	72·4	7·95	12·1	—	,,	,,	,,	,,	—
	Salt			9·35					9·2	
3	Base	75·0	9·3	9·9	—	$C_{16}H_{26}ON_2$	75·5	9·15	9·8	—
	Salt			8·1					7·8	
4	Base	—	—	11·1	13·95	$C_{14}H_{17}N_2Cl$	—	—	11·3	14·25
	Salt	52·4	6·1	8·6			52·3	5·95	8·7	—
5	Base	67·65	6·65	11·5	14·0	,,	67·6	6·9	11·3	14·25
	Salt	51·8	6·05	8·85	32·8		52·3	5·95	8·7	33·1
6	Salt	57·2	7·2	6·9	28·4	$C_{14}H_{17}N_2Cl$,2HCl	57·25	7·2	7·4	28·15
7	Base	—	—	18·3	—	$C_{16}H_{19}N_3$	—	—	18·3	—
	Salt	55·1	7·2	13·8	23·3	—	55·6	6·95	13·9	23·5
8	Salt	—	—	13·8	22·9	$C_{16}H_{19}N_3$,2HCl	—	—	13·9	23·5
9	Salt	—	—	11·4	—	$C_{15}H_{17}N_3$,2HCl	—	—	11·7	—

[a] "Salt" in this column = dihydrochloride. [b] Petrol = light petroleum (b. p. 40—60°). [c] After cyclisation of the crotonate, benzene was added to the Dowtherm which was then treated with hydrogen chloride. [d] Becomes red in air.

The author thanks Dr. A. J. Ewins, F.R.S., and Dr. J. N. Ashley, F.R.I.C., for their interest and advice, Mr. S. Bance, B.Sc., A.R.I.C., for the semimicroanalyses, Mrs. R. Stone, B.Sc., for the biological results, and the Directors of May & Baker Ltd. for permission to publish this work.

THE RESEARCH LABORATORIES, MAY & BAKER LTD.,
DAGENHAM, ESSEX.

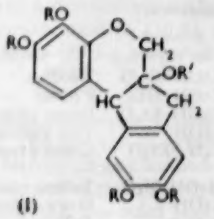
[*Received, October 23rd*, 1954; *resubmitted, April 12th*, 1956.]

640. *Some Reactions of Hæmatoxylin.*

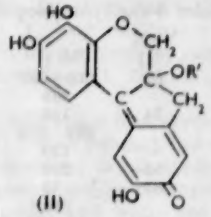
By D. J. DUFF.

Hæmatoxylin has been halogenated and methylated by indirect methods, and the products have been converted into the corresponding hæmatein derivatives. Benzylidenehæmatoxylin, its sulphonic acid, and anhydrohæmatoxylone have been prepared.

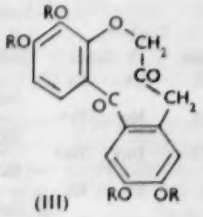
HÆMATEIN (II; R′ = H), the colouring matter of logwood, is not present in the fresh wood, but is derived by oxidation of colourless hæmatoxylin (I; R = R′ = H).[1] Oxidising agents generally convert hæmatoxylin into hæmatein (*e.g.*, for a preparation of hæmatein in good yield by alkaline peroxide see Giles *et al.*[2]). Diazonium salts readily oxidise hæmatoxylin to hæmatein, with quantitative evolution of nitrogen; aromatic nitroso-compounds in boiling alcohol also oxidise it, no azine being formed. Halogen derivatives cannot be prepared directly, but are readily obtained by halogenation of penta-*O*-acetylhæmatoxylin (I; R = R′ = Ac) followed by hydrolysis; oxidation then yields the crystalline hæmatein derivatives.



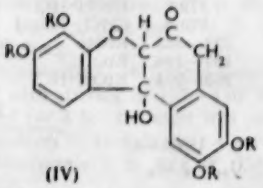
(I)



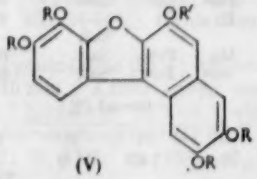
(II)



(III)



(IV)



(V)

The four phenolic hydroxyl groups in hæmatoxylin are more readily alkylated than the alcoholic hydroxyl group. Thus tetra-*O*-benzylhæmatoxylin may be prepared. Methylation of this product, and removal of the benzyl residues by hydrogenation leads to the impure *O*-methylhæmatoxylin (I; R = H, R′ = Me).

Hæmatoxylin condenses readily with aldehydes; benzylidenehæmatoxylin and its sulphonic acid are described in the Experimental section.

Tetra-*O*-methylhæmatoxylin (I; R = Me, R′ = H) with chromic acid yields tetra-*O*-methylhæmatoxylone (III or IV; R = Me) (Gilbody and Perkin;[3] for a synthesis see Pfeiffer *et al.*[4]). Treatment of this with acetic anhydride, followed by hydrolysis, yields

[1] For structures see Perkin and Robinson, *J.*, 1908, **93**, 489.
[2] Arshid, Desai, Duff, Giles, Jain, and MacNeil, *J. Soc. Dyers and Colourists*, 1954, **70**, 397.
[3] Gilbody and Perkin, *Proc.*, 1899, **15**, 27.
[4] Pfeiffer, Angern, Haack, and Willems, *Ber.*, 1928, **61**, 839.

anhydrotetra-*O*-methylhæmatoxylone (V; R = Me, R′ = H), a derivative of β-naphthol.[5] Penta-*O*-acetylhæmatoxylin and chromic acid yield tetra-*O*-acetylhæmatoxylone (III or IV; R = Ac);[6] this also yields an anhydro-derivative, hydrolysed by alkali to the parent substance anhydrohæmatoxylone (V; R = R′ = H), which readily forms azo-dyes.

Experimental

Monobromohæmatein.—Penta-*O*-acetylbromohæmatoxylin[7] (5 g.) was warmed with alcohol (25 c.c.) and 40% aqueous sodium hydroxide (10 c.c.) until dissolved. An equal volume of water was added, then 10-vol. hydrogen peroxide (10 c.c.). After a few minutes the solution was acidified with hydrochloric acid; the red *bromohæmatein* precipitated was collected, dried, and recrystallized from aqueous alcohol, forming red leaflets (1·8 g.), which shrink with charring at *ca.* 300°, but do not melt below 360° (Found: C, 48·0; H, 3·6; Br, 19·4; loss at 100°, 5·9. $C_{16}H_{11}O_6Br,H_2O$ requires C, 48·4; H, 3·3; Br, 20·2; H_2O, 4·5%).

Dibromohæmatein.—Penta-*O*-acetylhæmatoxylin (25 g.) in glacial acetic acid was treated with bromine (5·5 c.c.), the temperature being allowed to rise. After 2 hr. the solution was diluted with alcohol and poured into dilute sulphurous acid. The precipitate was dried and recrystallised from alcohol, then from acetone with addition of alcohol and water, forming needles of impure penta-*O*-acetyldibromohæmatoxylin (5 g.), m. p. 232—234° (Found: Br, 25·5. Calc. for $C_{26}H_{22}O_{11}Br_2$: Br, 23·9%). Hydrolysis and oxidation yielded *dibromohæmatein* as red leaflets, which char at *ca.* 250° but do not melt below 360° (Found: C, 41·0; H, 2·9; Br, 33·0; loss at 100°, 4·2. $C_{16}H_{10}O_6Br_2,H_2O$ requires C, 40·4; H, 2·5; Br, 33·6; H_2O, 3·8%).

Chlorohæmatein.—A slow stream of chlorine was passed through a solution of penta-*O*-acetylhæmatoxylin (10 g.) in acetic acid. *Penta-O-acetylchlorohæmatoxylin* (8·5 g.) separated as needles, m. p. 194° (Found: Cl, 6·55. $C_{26}H_{23}O_{11}Cl$ requires Cl, 6·50%). The product (5 g.) was hydrolysed and oxidised to chlorohæmatein (2·2 g.), lustrous red leaflets (from aqueous acetone) which shrink at *ca.* 300° but do not melt below 360° (Found: C, 55·2; H, 3·9; Cl, 9·6; loss at 100°, 6·75. Calc. for $C_{16}H_{11}O_6Cl,H_2O$: C, 54·5; H, 3·7; Cl, 10·1; H_2O, 5·1%).

Chlorotetra-O-methylhæmatoxylin.—(*a*) Tetra-*O*-methylhæmatoxylin (10 g.) was chlorinated in acetic acid, and the *product* isolated by addition of dilute sulphurous acid and recrystallised from alcohol as needles, m. p. 149—150° (Found: C, 61·5; H, 5·6; Cl, 9·1. $C_{20}H_{21}O_6Cl$ requires C, 61·2; H, 5·9; Cl, 9·0%).

(*b*) Penta-*O*-acetylchlorohæmatoxylin (10 g.) was mixed with warm alcohol, and 40% w/w aqueous potassium hydroxide (20 c.c.) and dimethyl sulphate (15 c.c.) were added alternately in portions. When the reaction subsided, the product was isolated in the same way as product (*a*), forming needles, m. p. 166—168° (Found: C, 61·5; H, 5·7; Cl, 8·7%), apparently an *isomer* of product (*a*).

Hydrolysis and methylation of penta-*O*-acetylbromohæmatoxylin yielded bromotetra-*O*-methylhæmatoxylin, colourless needles, m. p. 187—188°, identical with the product prepared by Pfeiffer *et al.*[8] from tetra-*O*-methylhæmatoxylin.

Tetra-O-benzylhæmatoxylin.—Perkin, Pollard, and Robinson[6] reported the preparation of this product without details; they described it as amorphous, but giving a crystalline acetyl derivative, m. p. 112°. The following method gave good results. Hæmatoxylin (30 g.) and benzyl chloride (50 c.c.) in methanol (250 c.c.) were brought to the b. p. under reflux, while nitrogen was passed through the solution to agitate it and maintain an inert atmosphere. Sodium hydroxide (16 g.) in methanol (250 c.c.) was dropped in during about 3 hr. Refluxing was continued for 1 hr. more, then the solvent was distilled off. The oily residue was dissolved in ether and washed with dilute alkali, water, and dilute sulphurous acid. The ethereal layer was separated and evaporated and the residue was steam-distilled to remove benzyl chloride. The residual *ether* solidified under cold water. It was dried and crystallised from acetone as needles (29 g.), m. p. 120°, rising to 130—140° on repeated recrystallisation (Found: C, 80·0; H, 5·95. $C_{44}H_{38}O_6$ requires C, 79·8; H, 5·7%).

The product (29 g.) was methylated by refluxing in dry benzene (300 c.c.) with powdered sodium methoxide (4·5 g.) and methyl iodide (12 c.c.) for 3 hr. The solution was filtered, benzene distilled off, and the residue recrystallised from acetone, forming needles (25·5 g.), softening about 60°, m. p. 120° (decomp.), of *tetra-O-benzyl-O-methylhæmatoxylin* (Found: C, 80·0; H, 5·95. $C_{45}H_{40}O_6$ requires C, 79·9; H, 5·9%).

[5] Perkin and Robinson, *J.*, 1909, **95**, 381.
[6] Perkin, Pollard, and Robinson, *J.*, 1937, 49.
[7] Buchka, *Ber.*, 1884, **17**, 683.
[8] Pfeiffer, Döring, Kobs, and Werner, *J. prakt. Chem.*, 1938, **150**, 199.

O-Methylhæmatoxylin.—The last ether (4 g.) and palladium oxide (0·2 g.) in ethyl acetate (100 c.c.) absorbed 500 c.c. of hydrogen in 4 hr. at room temperature. Removal of solvent left a reddish amorphous powder which was not obtained crystalline (m. p. 75—82°) (Found: OMe, 7·75. Calc. for $C_{16}H_{14}O_6$·OMe: OMe, 9·8%).

Oxidation with alkaline peroxide yielded impure *O*-methylhæmatein, a dark reda morphous powder, with tinctorial properties very similar to those of hæmatein. The substance does not melt below 360° (Found: C, 64·0; H, 5·4; OMe, 7·6. Calc. for $C_{16}H_9O_6$·OMe: C, 64·8; H, 4·5; OMe, 9·85%).

Benzylidenehæmatoxylin.—Hæmatoxylin (6 g.), alcohol (25 c.c.), water (25 c.c.), hydrochloric acid (2 c.c.), and benzaldehyde (1 c.c.) were mixed and boiled under reflux for 1 hr. On cooling, benzylidenehæmatoxylin (3 g.) separated. It forms colourless prisms (from alcohol), becoming red at 240°, then black and apparently melting with decomposition at 270°. The analysis suggests that the substance is the *pentahydrate*; it is unchanged at 100° (Found: C, 59·5; H, 5·5. $C_{30}H_{32}O_{12},5H_2O$ requires C, 59·9; H, 5·4%).

Sodium Benzylidenehæmotoxylinsulphonate.—Hæmatoxylin (3 g.), sodium *o*-formylbenzenesulphonate (1 g.), hydrochloric acid (2 c.c.), and water (20 c.c.) were refluxed for 1 hr. The oily *product*, after drying, crystallised from alcohol as red-tinted leaflets (0·9 g.) (Found: S, 3·9; Na, 2·7. $C_{30}H_{27}O_{15}SNa$ requires S, 4·05; Na, 2·9%).

Anhydrohæmatoxylone.—Penta-*O*-acetylhæmatoxylin is oxidised by chromic acid to tetra-acetylhæmatoxylone [6] (Found: C, 58·9; H, 4·2. Calc. for $C_{34}H_{30}O_{11}$: C, 59·5; H, 4·1%). Heating this with acetic anhydride and sodium acetate gave *penta-O-acetylanhydrohæmatoxylone*, needles, m. p. 258° (Found: C, 61·3; H, 4·0. $C_{26}H_{20}O_{11}$ requires C, 61·3, H, 3·9%), hydrolysed by aqueous-alcoholic alkali to *anhydrohæmatoxylone*, yellowish granules (from dioxan), darkening between 80° and 300°, but not melting below 360° (Found: C, 65·1; H, 3·4. $C_{16}H_{10}O_6$ requires C, 64·5; H, 3·4%).

Thanks are expressed to the British Dyewood Co. Ltd. for a maintenance grant to the Yorkshire Dyeware and Chemical Company for a gift of hæmatoxylin, and to Dr. (late Professor) W. M. Cumming and Dr. C. H. Giles for their helpful interest and advice.

Department of Technical Chemistry, Royal Technical College, Glasgow, C.1.
[Present address: The British Dyewood Co. Ltd., Glasgow, E.1.]

[*Received, April 22nd,* 1955.]

---

641. *Kinetics and Mechanism of Hydrochlorination of the Surface of Rubber Latex Particles.*

By Manfred Gordon and Thomas Carbarns.

A previously published technique for following the hydrochlorination of rubber particles in latex is applied to the particle surface locus mechanism, to which about three layers of polymer chains are accessible. The mechanism explaining the kinetics is based on a generalisation recently developed for extending the Hill–Hermans scheme of diffusion-reaction to the case of an unstable reagent. Here the double bonds of the polymer are regarded as fixed on a "liquid lattice," and a reactive species such as an ion pair [H_2Cl^+, Cl^-] diffuses in across the particle surface to react with these bonds. The reagent has a low equilibrium concentration in the aqueous phase ($\sim 10^{-13}$ mole/l.) and inside the non-polar polymer it has a short life-time ($\sim 10^{-9}$ sec.), during which it either "finds" a double bond, diffuses back into the aqueous phase, or decomposes to form inactive, covalent hydrogen chloride. This mechanism consistently interprets the effects on the rate of pressure, temterature, acidity, and particle size. A specially fine latex, of particle diameter $\sim$200 Å, was prepared in which nearly half the particle mass was accessible to the surface mechanism. The effect on the surface and bulk locus rates of admixture of sulphuric acid with the aqueous phase has been investigated.

Previous work [1] established that two reaction loci are involved in the hydrochlorination, vulcanization, and cyclization of natural and synthetic polyisoprene latices.

[1] (*a*) Crampsey, Gordon, and Sharpe, *J. Colloid Sci.*, 1954, **8**, 185; (*b*) Gordon and Taylor, *Proc. 3rd Rubber Technol. Conference, London*, 1954, 241.

These are the surface locus on the outside of the latex particles, and the bulk locus on the inside. In hydrochlorination, to be studied here in more detail, the two loci may react simultaneously under certain conditions, but are best isolated kinetically for separate study. At low pressure ($\leqslant$0·33 atm. at room temperature) the surface reaction occurs at measurable rate, while the bulk reaction is in practice immeasurably slow. At high pressures ($\geqslant$1 atm. at room temperature), the surface reacts too quickly for accurate measurement, and its reaction locus is manifest as a positive intercept P when the much slower, linear (zero order) bulk-rate curve is extrapolated to the composition axis (Fig. 1). Thus P measures the percentage of rubber coming within the range of the surface mechanism. For particles of sufficiently large radius r ($>$200 Å), P is proportional to the specific surface of the particles, or inversely to r. More precisely, when a distribution of particle sizes is present, the surface-average radius $\bar{r}$ is geometrically related to P thus :

$$\bar{r} = \tau/[1 - (1 - 0{\cdot}01P)^{\frac{1}{3}}] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where τ is the range or thickness of the layer accessible to the surface mechanism. This was determined [14] to be 15 Å through electron-microscopical calibration of $\bar{r}$, and this is the value of τ used here. In vulcanization τ was $<$15 Å and dependent on the conditions, but in cyclization of latex τ was much larger.[15] For the present work, a synthetic latex (Latex VI) of the finest particle size obtainable ($\bar{r} \sim$100 Å) was used in order to raise the accuracy of kinetic analysis. As shown by the intercept P (Fig. 1, curve *d*), nearly half the polymer mass was within range of the surface reaction mechanism for this latex.

Hill–Hermans diffusion of an unstable reagent.

A molecular mechanism, which has been discussed theoretically,[2] is here to be fitted to the surface rate curves (Figs. 2—6). The starting point is the basic mechanism [3] for polymer reactions controlled by diffusion across an interface. This concerns the diffusion from an aqueous " bath " into a polymer (muscle, resin, fibre, hide, gel, etc.) of reagent molecules which are instantaneously captured at a suitable site by chemical reaction in the polymer. The site is thereby inactivated to any reagent arriving subsequently. Such a process sets up a diffusion wave travelling into the polymer, with a rather sharp boundary between the layers of polymer sites which have or have not reacted. In the reaction under discussion the reagent is some species derived from hydrochloric acid, and the polymer sites are double bonds. Contribution to the reaction rate by segmental diffusion of polymer sites, to meet the incoming reagent, has been treated by Hermans [3] but the kinetic analysis given below suggests that such co-operation from the polymer is negligible in our reaction.

The *initial* rate of surface hydrochlorination (initial slope of Figs. 2—6) is very slow compared with other Hill–Hermans reactions. This observation can be satisfactorily reconciled with the mechanism just described provided that the concentration c of the reagent species in the aqueous phase is sufficiently small. However, the high reaction order (curvature) of the rate plot is totally irreconcilable with the theory, unless some new factor is introduced (Fig. 2) to account for the rapid deceleration of the diffusion wave-front on its way into the polymer. A general kinetic treatment has been derived [2] for any law fixing the relative rate constants of successive polymer layers which duly degenerates to ordinary (non-decelerated) Hill–Hermans diffusion for the particular law appropriate to it. The new factor causing the deceleration in surface hydrochlorination is taken to be the *instability* of the diffusing reagent. A parameter is introduced in the form of the stability constant s, which measures the fixed probability of a reagent molecule's surviving a diffusion jump from one polymer layer to the next without decomposition. It appears sound to expect that reagents originating in a highly polar aqueous medium and diffusing into a non-polar polymer should be susceptible to deactivation, decomposition, and neutralization. The rate curves can be well fitted (Fig. 2) on this basis, though, naturally, s has to be adjusted. The variable range of the surface locus

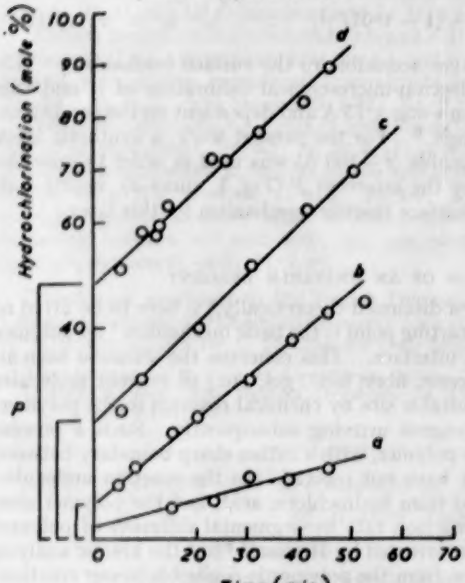
[2] Gordon, *Proc. Roy. Soc.*, 1955, *A*, **228**, 397.
[3] Cf. Hill, *ibid.*, 1928, *B*, **104**, 39; Hermans, *J. Colloid Sci.*, 1947, **2**, 387.

reactions is accommodated by the theory, in that s should vary from one reagent to another. In Fig. 2 the theoretical curves are seen to level off sharply after the equivalent of between one and four layers has reacted, according to the value chosen for the stability constant in the range $0 < s < 0{\cdot}6$.

We now summarize the essential mathematical theory of the kinetics of an unstable reagent in a Hill–Hermans reaction. For a plane interface, or spherical particles of $\bar{r}$ exceeding about 200 Å, the rate law becomes:

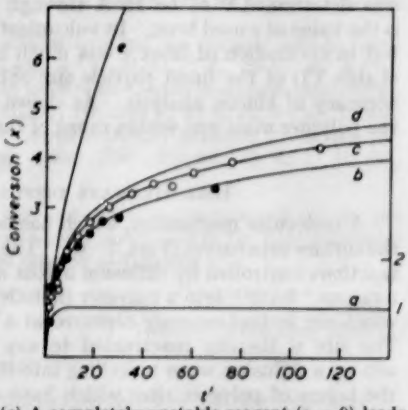
$$H = \sum_{i=1}^{\infty}\left(\sum_{a=1}^{\infty} C_{a,i,s}\right)[1 - \exp(-k_{i,s}\,t')] \quad . \quad . \quad . \quad . \quad . \quad (2)$$

FIG. 1. *Bulk locus rate curves* (300° K, 2 *atm.* HCl) *as a function of particle size.*



(*a*) Natural *Hevea* latex (surface average particle diameter ~4500 Å), (*b*) synthetic latex I (1175 Å), (*c*) synthetic latex II (467 Å), (*d*) synthetic latex VI (~180 Å). The intercepts P are a measure of the specific surface available to the immeasurably fast surface locus.

FIG. 2. *Theoretical surface locus rate curves* (*eqn.* 2) *for various reagent stabilities* s.



(*a*) A completely unstable reagent ($s = 0$) leads to a first-order reaction of the outermost layer only. (*b*) $s = 0{\cdot}6$. (*c*) $s = 0{\cdot}548$; ○ synthetic latex V, 69·9°, 167 mm. partial pressure of HCl. (*d*) $s = 0{\cdot}465$; ● synthetic latex V, 26·7°, 163 mm. partial pressure of HCl. (*e*) Hill–Hermans reaction of a completely stable reagent ($s = 1$).

The amount of reaction, measured in multiples of the complete reaction of the surface layer of polymer, is denoted by H. The constants $C_{a,i,s}$ are

$$C_{a,i,s} = \prod_{j=1}^{a} k_{j,s}/(k_{j,s} - k_{i,s}) \quad (i \neq j) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$C_{1,1,s} = 1$$

The rate constant $k_{i,s}$ refers to the i-th layer of polymer molecules from the interface; for the special case of instability of the reagent $k_{i,s}$ is given thus as a function of s:

$$k_{i,s} = \sinh(\operatorname{sech}^{-1} s)/\sinh(i \operatorname{sech}^{-1} s) \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The dimensionless "time" unit t' is related to the time t in seconds through the unknown

FIGS. 3 and 4. *Invariance of the shape of the surface rate curves under a change in* HCl *pressure.*

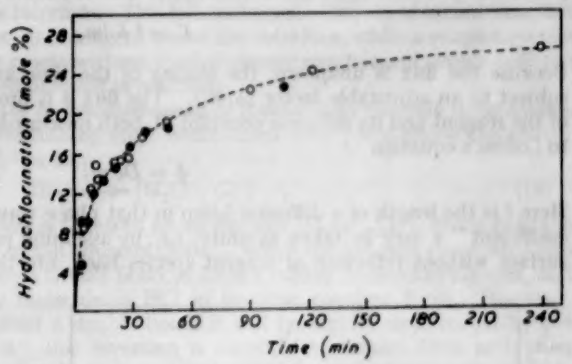


FIG. 3.

Synthetic latex V, 300° K, ○ 249 mm. partial pressure of HCl; ● 163 mm. (measured times multiplied by 0·448).

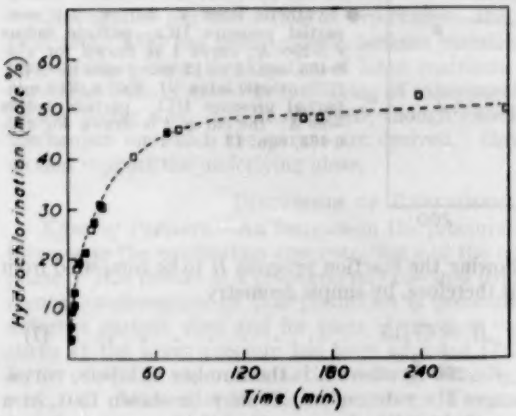
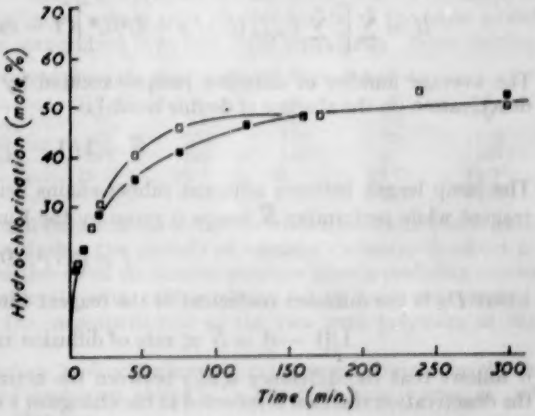


FIG. 4

Synthetic latex VI, 300° K, □ 249 mm. partial pressure of HCl; ■ 57 mm. (measured times multiplied by 0·1105).

FIG. 5. *Effect of sulphuric acid on the surface locus hydrochlorination rate.*

□ Synthetic latex VI, 249 mm. partial pressure of HCl; ■ the same in presence of 17% H_2SO_4.



gross inward flux ϕ in moles of reagent per sec. per cm.^{2} of surface, and to the number m_1 ($\sim 6 \times 10^{-6}$) of moles of unsaturation in one cm.^{2} of rubber surface:

$$t' = t\phi/m_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Because the flux is unknown, the scaling of the time axis of our experimental plots is subject to an adjustable factor (ϕ/m_1). The flux ϕ is proportional to the concentration c of the reagent and its diffusion constant D, both measured in the aqueous phase, according to Collins's equation

$$\phi = Dc\,\alpha/l \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Here l is the length of a diffusion jump in that phase (say 1 Å), and the "accommodation coefficient" α may be taken as unity, *i.e.*, by assuming perfect absorption at the particle surface without reflection of reagent species back into the water. The spacing between

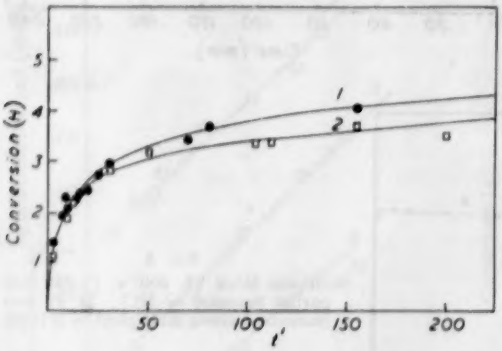


FIG. 6. *Effect of particle curvature on surface locus rate curve.*

● Synthetic latex V, 300° K, 249 mm. partial pressure HCl; particle radius $r > 200$ Å; curve 1 is drawn for $s = 0{\cdot}465$, eqn. 2 or 12 being used ($L > 40$). □ Synthetic latex VI, 300° K, 249 mm. partial pressure HCl; particle radius ~ 90 Å; the curve 2 is drawn for $s = 0{\cdot}465$, eqn. 12 ($L = 18$).

rubber chains is 5 Å. The relation allowing the reaction progress H to be computed from the measured fractional conversion C is therefore, by simple geometry:

$$H = C\bar{r}/15 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

For particles of $L < 40$ layers (*i.e.*, $\bar{r} < 200$ Å) where L is the number of layers, curvature of the interface progressively changes the rate curve. It may be shown that, as a first approximation, eqn. (2) may be amended to allow for curvature, thus

$$H = \sum_{i=1}^{\infty}\left[\sum_{a=1}^{\infty} C_{a,i,s}\,(L - a + l)^2/L^2\right]\left\{1 - \exp[-k_{i,s}\,t'L^2/(L - i + l)]\right\} . \quad (8)$$

The average number of diffusion jumps executed by the reagent in the polymer before deactivation (in the absence of double bonds) is

$$\bar{N} = 1/(1 - s) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

The jump length between adjacent rubber chains being 5 Å, the average lifetime of the reagent while performing $\bar{N}$ jumps is given by the Einstein law

$$\bar{t} = (5\bar{N})^2/2D_R \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where D_R is the diffusion coefficient of the reagent through the polymer. Since

$$1/(1 - s) = \bar{N} \propto \text{rate of diffusion/rate of deactivation} \quad . \quad . \quad . \quad (11)$$

it follows that the difference $\delta(\Delta E)$ between the activation energies for diffusion and for the deactivation reaction is reflected in the change of s with temperature, thus

$$\delta(\Delta E) = -2{\cdot}3R\,\delta \log[1/(1 - s)]/\delta(1/T) \quad . \quad . \quad . \quad . \quad . \quad (12)$$

The model on which the kinetic theory had been derived implies that the rate-controlling transition state of the surface reaction is the passage of the reagent species from the water phase to the polymer through the interface. This follows because the rate of surface reaction is proportional to the flux ϕ (eqn. 5) of reagent across the interface, while a reagent species once arrived within the polymer reacts without further energy requirement, every collision with a double bond being assumed to result in reaction.

Application of the Theory to the Hydrochlorination of Rubber.—In the *bulk* locus hydrochlorination reaction, the rate-controlling step, which must take place inside the rubber phase, was previously suggested [4] to be :

$$2HCl \longrightarrow [H_2Cl^+, Cl^-] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

The reagent in the *surface* reaction is taken to be an ion pair $[H_2Cl^+, Cl^-]$, which exists in low equilibrium concentration c in the aqueous phase. When the ion pair penetrates into the rubber, it is " snapped up " by a double bond to form a rubber hydrochloride unit, and to liberate the proton-solvating molecule of HCl in inactive, covalent form. However, if the reagent ion pair fails to meet a double bond, it will be rapidly deactivated by the reverse reaction to its formation : this reversion is expected to require little activation energy. It is this rapid deactivation to form two molecules of covalent hydrogen chloride which restricts the range of the surface reaction.

Throughout our theoretical interpretation, the adsorbed layer of non-ionic stabiliser (Vulcastab LW) has been ignored, because variations in the nature and concentration of the stabilizer leave the kinetics of latex reactions unaffected.[5] Because two adjustable parameters are involved in the fitting of experimental curves (Figs. 2—6), *viz.*, s and the scaling factor ϕ/m_1, the fit obtained, though excellent, cannot be taken to establish the mechanism on which the curves are derived. However, the effects studied in the next section support the underlying ideas.

Discussion of Experimental Results

Effect of Pressure.—An increase in the pressure of hydrogen chloride is reflected in an increase in the equilibrium concentration c of the reagent species (ion pair) in the aqueous phase. This results in a proportionate rise in ϕ (eqn. 6), and hence in t' (eqn. 5). Experimental confirmation of this prediction is presented in Figs. 3 and 4 for two latices of different particle sizes and for pairs of pressure values. In each case, the experimental curve at the lower pressure has been adjusted (Table) by multiplication with a suitable factor of all the experimental time values, whereby the curve is brought into coincidence with that obtained at the higher pressure. The scaling factor is equal to the ratio of the two flux rates. This finding provides confirmation of the irrelevance of diffusion of rubber segments to the interface. Since the flux of the reagent species alone controls the shape of the rate curve, the assumption of *stationary* rubber sites (double bonds) in the basic model is vindicated. The adequacy of the assumption is at first sight surprising. Some mixing

Apparent flux rates of reagent from the time scales of Figs. 3 and 4.

Figure	3	4	3	4	6
Latex	V	VI	V	VI	V
Total pressure (H_2O + HCl) (mm. Hg)	255	255	170	65	255
Partial pressure of HCl (mm. Hg)	249	249	163	57	167
Temperature	26·7°	26·7°	26·7°	26·7°	69·9°
Flux (ϕ/m_1) (min.$^{-1}$)	0·67	0·67	0·30	0·074	0·30

with the original polymer by segmental diffusion of rubber hydrochloride units which have reacted might be expected to occur during the periods of minutes or hours involved in the rate curves. The success of the theory of stationary polymer sites is probably due to the immiscibility of rubber hydrochloride with rubber chains which have not reacted. Independent observations confirm the incompatibility of the two pure polymers at the reaction temperature.

Both the isolated bulk and surface hydrochlorination rates vary approximately as powers of the partial pressure p of hydrogen chloride. The bulk rate varies as $p^{3/2}$

[4] Crampsey, Gordon, and Taylor, *J.*, 1953, 3925.
[5] Cf. Gordon, *Ind. Eng. Chem.*, 1951, **43**, 386.

according to the slope of the logarithmic plot (II, Fig. 7) over the range 760—1900 mm. This plot refers to measurements on natural (*Hevea*) latex, but syntheric polyisoprene gives results in close agreement.[15,4] The surface hydrochlorination rate, according to plot II (Fig. 7), varies only as $p^{1.6}$ or thereabouts. A dependence of the rate on p^2 would be predicted if the diffusion flux ϕ of the reactive ion pair $[H_2Cl^+, Cl^-]$ is assumed to be strictly proportional to its thermodynamic activity. As this assumption is, at best, approximate, the small discrepancy is of no consequence.

Mean Life-time and Concentration of the Transient Reagent Species.—The experimental curves (Fig. 2) require values of $s \sim 0{\cdot}5$ to fit the kinetic theory. Equation 9 shows that the reagent species is deactivated on the average after two diffusion jumps in the polymer, *i.e.*, after describing a diffusion path of 10 Å. The diffusion coefficient D_R of the ion-pair reagent is estimated to be $1{\cdot}5 \times 10^{-6}$ cm.^{2}/sec. from Grün's measurements [6] on substances of various molecular weights diffusing through rubber. Equation 10 then leads to an average mean life-time of the ion-pair reagent of only 3×10^{-9} seconds. The experimental values of ϕ/m_1 (Table), taken with eqn. 6, lead to estimates of 6×10^{-13} to 6×10^{-12} moles/l. for the concentration of the reagent ion pair in the aqueous phase between 50 and

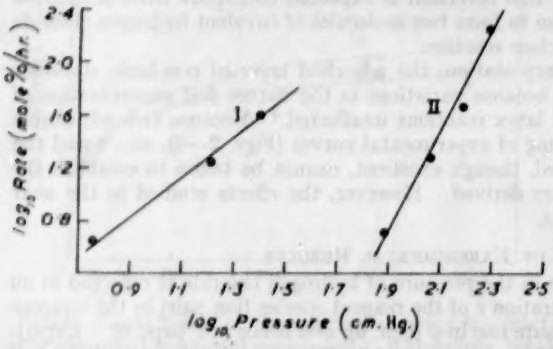


FIG. 7. *Pressure dependence of surface and bulk locus rates.*

(I) Initial surface locus rate (100 ϕ/m_1 hr.$^{-1}$). (II) Unretarded zeroth order bulk locus rate.

250 mm. Hg of hydrogen chloride. (For this calculation, the diffusion coefficient D of the reagent through the aqueous phase is taken as that valid for hydrogen chloride itself, *i.e.*, $2{\cdot}5 \times 10^{-5}$ cm.^{2}/sec.) For comparison with the estimates of the ion-pair concentration, we quote estimates ranging from $5{\cdot}9 \times 10^{-12}$ to 4×10^{-8} moles/l. for undissociated hydrochloric acid, as distinct from ion pairs, in 0·01—1·0N-HCl.[7] The calculations of this section illustrate the fact that surface hydrochlorination depends on the thermal bombardment of the rubber surface by a short-lived and dilute reagent.

Effect of Admixture of Sulphuric Acid.—Reductions of the overall concentration of hydrogen chloride in water can be made, at constant hydrogen chloride pressure, by admixture of sulphuric acid, an acid somewhat stronger than hydrochloric acid at equal concentration. At high concentration of sulphuric acid, incursion of the acid-catalyzed cyclization of rubber as a side reaction is to be feared, whose rate (in the absence of hydrogen chloride) becomes measurable above about 60% of H_2SO_4 in the aqueous phase.[8] We have, therefore, compromised by studying the effect on the kinetics of hydrochlorination of an aqueous phase composed of 17 : 83 H_2SO_4–H_2O (w/w). As shown in Fig. 5, this appreciable change in the acidity of the original aqueous medium produces very little change on the surface hydrochlorination rate. The initial rate is unchanged within the small experimental error. Indeed, the only alteration in the rate curve due to the addition of sulphuric acid is a moderate variation which appears in the middle range and remains unexplained.

The activity of water must be expected to vary considerably when 17% of sulphuric acid is added. The invariance of the hydrochlorination rate shows that the equilibrium

[6] Grün, *Experientia*, 1947, **3**, 491.
[7] Wolfenden, *Ann. Reports*, 1932, **29**, 21.
[8] Gordon, *Proc. Roy. Soc.*, 1951, *A*, **204**, 569.

concentration c of the reagent species depends only on the activity (vapour pressure) of hydrogen chloride, and not on the activity of water. This confirms that the reagent is formed from an integral number n of HCl units, and thus carries no net ionic charge, in conformity with eqn. 13.

Effect of Temperature.—At constant pressure, the *bulk* locus hydrochlorination reaction has an apparent negative activation energy [4] of −6 kcal./mole. In contrast, the *surface* hydrochlorination rate dH/dt' is found to be virtually independent of temperature, as well as of added sulphuric acid. The initial rate does not vary measurably at three temperatures over the 42° range studied (a curve at 44° has been omitted from Fig. 2). The estimated accuracy of these measurements leads to the limits $E = 0 \pm 1{\cdot}5$ kcal./mole for the activation energy. This means that the energy state of the reagent, when passing through the rubber surface, is practically on a level with the corresponding number of covalent molecules of hydrogen chloride in the gas phase. Thus, when passing into the rubber, the reagent must be largely stripped of its hydration shell, which supports the conclusion that it does not contain water. The shape of the rate curve does change slightly, but definitely, with temperature, in a way accommodated by the theory. Plots b and c in Fig. 2 interpret the change in shape between 26·7° and 69·9° as a change of the order of 20%

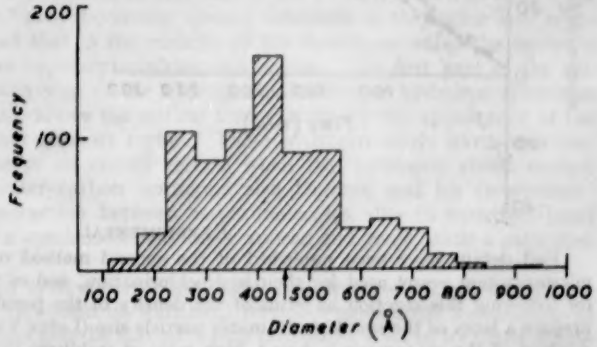


FIG. 8. *Apparent size distribution curve of the 791 particles on a micrograph of synthetic latex VI, shadow cast with Au/Pd alloy. The calculated apparent surface average diameter is marked by an arrow.*

in the stability constant s. According to eqn. 12, this corresponds to a value of $\delta(\Delta E) \sim 1$ kcal. Such a small difference between the energies of diffusion and of the deactivation process reflects the fact that both these energies should, in theory, be individually small.

Effect of Curvature.—Even for the smallest particles available (Latex VI), the expected effect of curvature on the surface hydrochlorination kinetics is not yet very appreciable. Fig. 6 suggests that the observed deviations of the rate curve of Latex VI are in the expected sense and of the right order of magnitude. To show this, we have drawn plot 2 as the theoretical curve of eqn. 8 with $L = 18$ (*i.e.*, $\bar{r} = 90$). The actual radius $\bar{r}$ of Latex VI is 76—110 Å. The heterodisperse nature of the latex (Fig. 8) would have to be taken into account if the theory were to be refined beyond the first approximation inherent in eqn. 8. The accuracy of the present results does not warrant such refinements.

Effect of Sulphuric Acid on the Bulk Rate.—It was found (Fig. 5) that the presence of 17% of sulphuric acid in 83% of water affected the surface locus rate curves negligibly. The presence of a similar percentage (20%) of sulphuric acid exerts only a small deceleration of the bulk locus reaction measured at 2 atm. of HCl. However, as shown in Fig. 9, this effect takes an interesting form when natural (*Hevea*) latex is used, which confirms the interpretation given [9] of the early linear slow portion of the rate curve, which is observed only with natural latex. It was suggested that this latex contains a retarder which deactivates a fixed number of the ion-pair reagents in the bulk locus reaction, before the full linear rate curve takes over at the " kink." The figure shows that slope of the retarded portion preceding the kink is not measurably affected by sulphuric acid, while the subsequent, unretarded, portion is definitely reduced in slope (rate). In accordance

[9] Gordon and Taylor, *J. Appl. Chem.*, 1955, **5**, 62.

with the theory of retardation given by Gordon and Taylor,[9] the two unretarded rate lines extrapolate back to the point −27% on the conversion axis, as did six curves obtained by these authors under a wide variety of HCl pressures and temperatures. The constant negative intercept of the unretarded rate line is interpreted as the integrated total of the retardation effect, just as the positive intercept of the retarded rate plot (preceding the kink) is interpreted as the measure of the fast surface reaction.

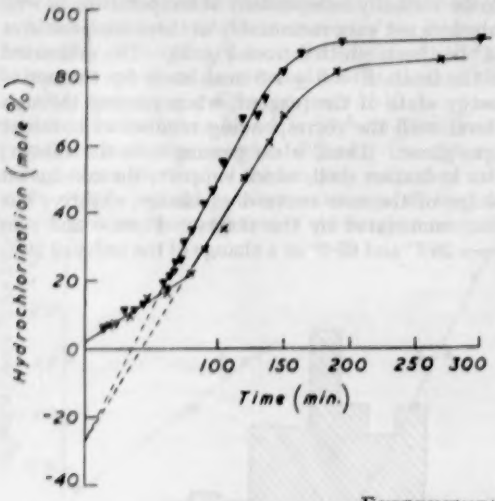


FIG. 9. *Effect of sulphuric acid on the bulk locus rate of hydrochlorination at* 300° K *and* 2 *atm. of* HCl.

▲ In absence of H_2SO_4; × in presence of 20% H_2SO_4.

EXPERIMENTAL

Full details have been published of the general method of preparing the latices, of the micro-reaction vessel used for their hydrochlorination, and of the density gradient technique for following this reaction in terms of the density of the purified polymer.[1b,4,9] In order to prepare a latex of the smallest attainable particle size (Latex VI) a higher temperature, greater dilution of the monomeric isoprene, high ratio of stabilizer (Vulcastab LW) to isoprene, and shorter polymerisation time than usual were employed. These factors favour the production of finer particles in emulsion polymerization.[10] The detailed formulation of Latices V and VI were respectively: isoprene 10 g., 1·4 g.; water 15 g., 20 g.; 20% Vulcastab LW in water 4 g., 4 g.; ammonium persulphate 0·25 g., 0·05 g. The reagents were sealed in glass ampoules under carbon dioxide and shaken at 49° for 9·5 hr. (Latex V) and 60° for 2 hr. (Latex VI).

The usual size determination from the intercept P and eqn. (1) gave a value of $\bar{r} = 230$ Å for Latex V. For Latex VI this method leads to $\bar{r} = 76$ Å. Attempts to verify this value by direct electron microscopical determination encountered some difficulty. The small particles were insufficiently well resolved for size measurement without metal shadowing. Shadowing did give excellent resolution, but the results so obtained are known to be too high. The correction applicable for larger particles[1a] consists in subtracting 115 Å from the measured radius, in agreement with findings by Kern and Kern[11] for polystyrene latex. Statistical evaluation of the 791 particles visible on a shadowed micrograph gave a distribution curve (Fig. 8) much less sharp than those of the coarser Latices I—V, with an uncorrected value of $\bar{r} = 226$ Å. Application of the correction mentioned leads to $\bar{r} = 111$ Å. While this agrees reasonably with the value of 76 Å from the intercept P and with the kinetic effect due to curvature (Fig. 6), the correction here exceeds the radius of the smallest shadowed particles visible, which throws some doubt on its validity in the range of very small particles.

We thank Professor P. D. Ritchie for his interest, and Mr. J. W. Sharpe for taking the electron micrograph underlying Fig. 8.

DEPARTMENT OF TECHNICAL CHEMISTRY,
ROYAL TECHNICAL COLLEGE, GLASGOW. [*Received, January 30th,* 1956.]
[*Present Address* (M. G.): COLLEGE OF SCIENCE AND TECHNOLOGY, MANCHESTER.]

[10] Harkins, *J. Amer. Chem. Soc.*, 1947, **69**, 1428.
[11] Kern and Kern, *J. Appl. Phys.*, 1950, **21**, 705.

642. *Statistical Thermodynamic Interpretation of the Sorption of Water and Methanol by Carbon.*

By R. M. Barrer and W. I. Stuart.

When the statistical thermodynamic treatment of localised sorption with interaction is applied to the characteristic sigmoid isotherms of water and of methanol on carbon below the monolayer value, it is found to describe the isotherms (*i.e.*, the free energy of sorption) reasonably for all save, in some cases, small values of θ. The analysis shows that exothermic lateral interaction, though present, is so small as to rule out normal intermolecular hydrogen bonds. On the other hand, the energy of binding to the sorbent surface is adequate for two hydrogen bonds between a sorbate molecule and the surface in the case of water, and for one such bond for methanol together with a more substantial contribution of dispersion forces.

It has been shown [1] that water isotherms in charcoal, which are well known to be of Type V in Brunauer's classification,[2] give the strong upward inflexions in the region well *before* a monolayer is completed, and that in the vicinity of the monolayer value the isotherm flattens to some extent before capillary condensation begins. The first part of the isotherm therefore recalls the behaviour of the hydrogen–palladium or hydrogen–zirconium system, at temperatures a little above the critical temperature for the appearance of the well-known two-phase invariant-pressure region. These hydrogen alloys have been successfully interpreted in terms of an energy release when two hydrogen atoms occupy adjacent sites.[3,4] For the water–carbon isotherms also Dubinin and his co-workers [1] postulate a strong lateral interaction between water molecules, due to hydrogen-bond formation, so that islands of a condensed monolayer appear and grow, until a saturated monolayer is completed.

Although the two kinds of system—hydrogen–alloy and water–charcoal—are physically very distinct, from the viewpoint of statistical thermodynamics the formulation of the respective sorption isotherms may be similar. One postulates a set of localised homogeneous sorption sites, whether inside the sorbent or on its surface, and an interaction energy $2w/Z$ per pair of atoms or molecules adsorbed on adjacent sites. Z denotes the co-ordination number of a site. Then an isotherm for sorption without dissociation is obtained : [5]

$$K = \frac{\theta}{p(1-\theta)}\left(\frac{2(1-\theta)}{\beta+1-2\theta}\right)^z \quad \ldots\ldots\ldots \quad (1)$$

Here p denotes the equilibrium pressure, and θ is the fraction of all the available sites which are occupied. The quantity $\beta = \left\{1 - 4\theta(1-\theta)[1-\exp-(2w/ZkT)]\right\}^{\frac{1}{2}}$, and K is a constant which can be explicitly evaluated for the various possible degrees of freedom of the sorbed molecules and the same for all values of w, including zero.* We have used the model for localised sorption with interaction to investigate water–carbon isotherms,

* For example, for an oscillator vibrating with mean frequency $\bar{\nu}$ and of mass m,

$$K = \frac{1}{kT}\left(\frac{kT}{2\pi m}\right)^{3/2}\frac{1}{\bar{\nu}^3}\exp \chi/RT$$

where k is the Boltzmann constant and χ is the least energy required to remove an Avogadro number of oscillators into the gas phase from the sorbent, in absence of lateral interaction (see also eqn. 5). If one defines a sorption heat by $\partial \ln K/\partial T = \Delta H_1/RT^2$, then $\Delta H_1 = \chi + \frac{1}{2}RT$.

[1] Dubinin, Zaverina, and Serpinksky, *J.*, 1955, 1760.
[2] Brunauer, "The Adsorption of Gases and Vapours," Oxford Univ. Press, 1944, Chapter 6.
[3] Lacher, *Proc. Roy. Soc.*, 1937, *A*, **161**, 525.
[4] Martin and Rees, *Trans. Faraday Soc.*, 1954, **50**, 343.
[5] Fowler and Guggenheim, "Statistical Thermodynamics," Cambridge Univ. Press, 1939, p. 441.

and to examine further the hypothesis that the water molecules are interlinked, and condense, by hydrogen bonding.[1] It is known that the strength of the hydrogen bond between water molecules is about 5·5 kcals.[6] The methanol–carbon isotherm [7] also behaves similarly to the water–carbon one, and will likewise be examined in terms of the above model.

Free-energy Relations.—In the Figure are shown experimental isotherms, and isotherms calculated according to eqn. 1, by the following procedure. The v_m, or monolayer, value was chosen (Table 1, column 2). Then if $p(\frac{1}{2})$, $\beta(\frac{1}{2})$ denote the values of p and of β when $\theta = \frac{1}{2}$, we have

$$p(\tfrac{1}{2}) = \frac{1}{K}\left(\frac{1}{\beta(\frac{1}{2})}\right)^z = \frac{1}{K}\exp\left(+\frac{w}{kT}\right) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

so that

$$\frac{p}{p_0} = \frac{p(\frac{1}{2})}{p_0}\,\frac{\theta}{(1-\theta)}\left(\frac{2-2\theta}{\beta+1-2\theta}\right)^z \exp\left(-\frac{w}{kT}\right) \quad . \quad . \quad . \quad . \quad (3)$$

where p_0 denotes the saturation pressure of the liquid sorbate. Then, from the experimental isotherm and v_m, $p(\frac{1}{2})/p_0$ was read off. For example, for one particular water–carbon [1] isotherm $p(\frac{1}{2})/p_0$ was 0·43. Values of w/kT were then selected, and used, together with likely values of Z, to give the best agreement of the experimental and the calculated isotherm.

Although v_m might have been determined by some traditional method, such as the B.E.T. plot, it is clear that this procedure is basically wrong for adsorption in a monolayer obeying eqn. 1. We have therefore chosen v_m by inspection and refined its value by trial, in association with the similarly selected and refined values of w/kT, so that the best result was obtained. All relevant numerical data for the best agreement are summarised in Table 1.

TABLE 1. *Analysis of sorption of water and methanol on carbon in terms of equation* 1.

System	Monolayer value (moles/g.)	Temp.	Z	$-2w/Z$ (cal./Avogadro no. of mol. pairs)	$-w/kT$	10^3K from exptl. curves	$10^{13}K_0$ from exptl. curves	$-\Delta H$ or $-\Delta H_1$ (kcal./mole)	$\bar{\nu}$ (10^{13} sec.$^{-1}$) * (*A*)	(*B*)
H_2O–channel black [1]	1·5	20°	6	400	2·0	1·35	—	10·7 (ΔH)	—	—
	1·5	20	4	640	2·2	1·12		,,		
	1·5	20	3	930	2·7	0·91		,,		
	1·5	20	2	1750	3·0	0·50		,,		
H_2O–sugar charcoal [8]	10·3	0	6	410	2·28	3·49	1·37	10·5 (ΔH_1)	0·73	0·98
	10·3	100	6	550	2·23	0·0190	1·33	,,	0·81	1·25
	10·3	0	4	700	2·60	2·53	0·99	,,	0·77	1·09
	10·3	100	4	760	2·40	0·0134	0·75	,,	0·88	1·50
CH_3OH–graphite [7]	0·06	0	6	325	1·80	1·45	—	9·0 (ΔH)	—	—
	0·06	0	4	540	2·0	1·18		,,		

* (*A*) Non-rotating vibrator; (*B*) freely rotating vibrator.

The Figure shows that localised adsorption with interaction gives a satisfactory description of the isotherms of water and of methanol, for values of θ corresponding to the upward inflexion of the isotherm to values approaching 1. However, eqn. 1 is sometimes unable to express the experimental contour of the isotherm for water when θ is small. The isotherms shown in the Figure have been calculated by taking $Z = 6$ (close packed monolayer) and $Z = 4$ (square array). In addition, the interaction energy $2w/Z$ has been evaluated for water for $Z = 3$ (triangular array such as might be expected for lateral hydrogen bonding) and even $Z = 2$ (linear array). Interaction energies are of appreciable magnitudes, but are much less than that of normal hydrogen-bond formation in water.

Energy Considerations.—From the temperature coefficients of K in eqn. 1 a heat ΔH_1 may be obtained, defined by $\partial \ln K/\partial T = \Delta H_1/RT^2$. This heat measures the interaction

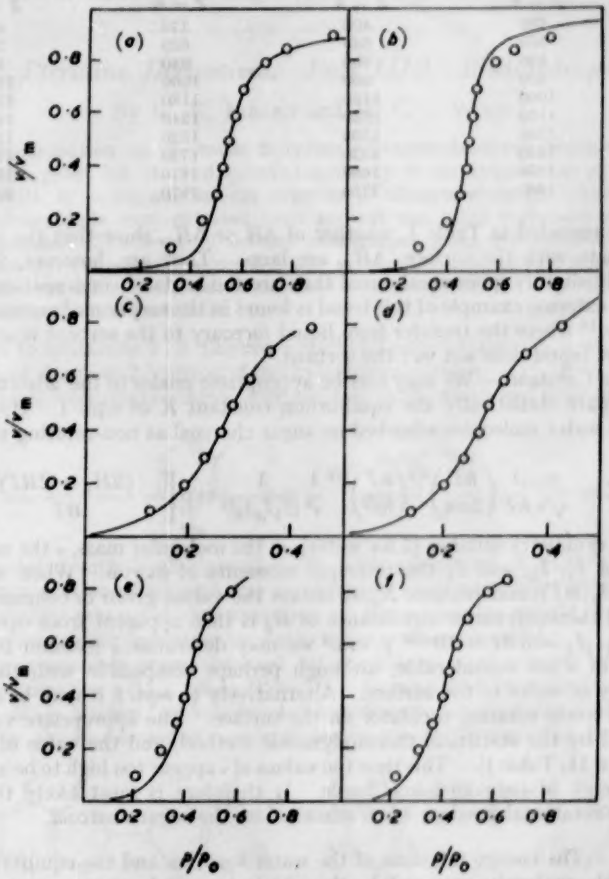
[6] Stuart, "Die Struktur des freien Molekuls," Springer, Berlin, 1952, p. 49.
[7] Pierce and Smith, *J. Phys. Chem.*, 1950, **54**, 356.
[8] Coolidge, *J. Amer. Chem. Soc.*, 1927, **49**, 715.

between sorbate molecules and the sorbing surface without including the contribution of lateral interaction. ΔH_1 is not identical with the isosteric heat ΔH $[(\partial \ln p/\partial T)_\theta = \Delta H/RT^2]$ which does include lateral interaction. From eqn. 1 we have :

$$(\partial \ln p/\partial T)_\theta = -(\partial \ln K/\partial T)_\theta - Z[\partial \ln (\beta + 1 - 2\theta)/\partial T]_\theta \quad . \quad . \quad . \quad (3)$$

or, since $\partial \ln K/\partial T$ is independent of the amount sorbed,

$$\Delta H = \Delta H_1 - ZRT^2[\partial \ln (\beta + 1 - 2\theta)/\partial T]_\theta \quad . \quad . \quad . \quad . \quad . \quad (4)$$



Adsorption isotherms for : (a) water on sugar charcoal at 100°, $Z = 6$; (b) water on sugar charcoal at 0°, $Z = 4$; (c) methanol on graphite at 0°, $Z = 6$; (d) methanol on graphite at 0°, $Z = 4$; (e) water on channel black at 20°, $Z = 6$; and (f) water on channel black at 20°, $Z = 4$.

The subscript a denotes that differentiation is carried out while keeping constant the amount sorbed, and so also for the model used, θ. The second term on the right-hand side of eqn. 4 represents the contribution of lateral interaction (Table 2).

Values of K (Table 1, column 7) were obtained from eqn. 2, for the appropriate value of w/kT (column 6). For the water–sugar charcoal system the results at 0° and at 100° serve to determine $\Delta H_1 = -10{\cdot}5$ kcal./mole. To obtain calculated isosteric heats lateral contributions must be added. These are similar on sugar charcoal and on channel black, according to the values of w/kT of Table 1, and are given for channel black in Table 2.

The isosteric heat of −10·7 kcal./mole for channel black [1] depends little upon θ for intermediate and larger values of θ, and does not show the required rise due to interaction, either because of a compensating fall due to some heterogeneity of sites or because the data are not accurate enough to disclose the rise. The isosteric heat for the methanol–graphite system is also nearly independent [7] of film density for larger values of θ.

TABLE 2. *Calculated lateral-interaction energies (cal./mole).*

	Energy for CH_3·OH–graphite [7] at 0°		Energy for H_2O–channel black [1] at 20°	
θ	$Z = 6$	$Z = 4$	$Z = 6$	$Z = 4$
0·1	290	400	370	490
0·2	500	640	620	780
0·3	680	800	840	970
0·4	830	950	1000	1130
0·5	1000	1150	1180	1280
0·6	1150	1220	1340	1430
0·7	1280	1360	1520	1590
0·8	1450	1530	1720	1790
0·85	1560	1680	1810	1910
0·9	1660	1750	1970	2060

The values recorded in Table 1, whether of ΔH or ΔH_1, show that the heats of interaction of sorbate with the surface, ΔH_1, are large. They are, however, for a range of values of θ only slightly more exothermal than are the heats of condensation of the liquid sorbates. An extreme example of this trend is found in the sorption of mercury on carbon [9] or in chabazite,[10] where the transfer from liquid mercury to the sorbent is an endothermal process and the liquid does not wet the sorbent.

Equilibrium Constants.—We may ascribe appropriate modes to the adsorbed molecules, and then evaluate statistically the equilibrium constant K of eqn. 1. If, for instance, we regard the water molecules adsorbed on sugar charcoal as non-rotating vibrators, then the result is :

$$K = \frac{\sigma}{\sqrt{\pi}} \frac{1}{kT} \left(\frac{kT}{2\pi m}\right)^{3/2} \left(\frac{kT}{8\pi^2}\right)^{3/2} \frac{1}{\bar{\nu}^6} \frac{1}{(I_1 I_2 I_3)^{\frac{1}{2}}} \exp\left[-\frac{(\Delta H_1 - 2RT)}{RT}\right] \quad . \quad (5)$$

where σ is the symmetry number (2 for water), m the molecular mass, $\bar{\nu}$ the mean vibration frequency, and I_1, I_2, and I_3 the principal moments of inertia. When we write $K = K_0 \exp[-(\Delta H_1/RT)]$ and evaluate K_0 we obtain the values given in column 8 of Table 1. The statistical thermodynamic significance of K_0 is then apparent from eqn. 5, and since for water,[11] $I_1 I_2 I_3 = 5{\cdot}67 \times 10^{-120}$ g. cm.^{2} we may determine $\bar{\nu}$ (column 10 of Table 1). These values of $\bar{\nu}$ are considerable, although perhaps compatible with the rather high bonding energy of water to the surface. Alternatively to eqn. 5 it may be supposed that the water is a freely rotating oscillator on the surface. The appropriate value of K was again obtained by the statistical thermodynamic method, and the value of $\bar{\nu}$ determined from it (column 11, Table 1). This time the values of $\bar{\nu}$ appear too high to be associated with a bonding energy of only 10·5 kcal./mole. It therefore is most likely that the water molecules lose rotational freedom when adsorbed on the sugar charcoal.

Discussion.—The energy relations of the water sorption and the equilibrium constants are such that the molecules may well be thought to have at least two-point attachment to the surface through hydrogen bonds and mirror-image forces. Attachment may be to chemisorbed oxygen atoms or to carbon atoms of graphite-like layers. The total heat of attachment, ΔH_1, happens to be rather near to that of two –O–H···O=C< bonds. Methanol can form only one hydrogen bond with the surface, but the dispersion-force interaction with the sorbent should be substantially larger than for water.

The analysis shows that if true hydrogen bonds occur in the first layer they arise between sorbate and sorbent and not between the sorbate molecules themselves. Interaction energies, while exothermal and reasonably able to account for the upward inflexion

[9] Coolidge, *J. Amer. Chem. Soc.*, 1927, **49**, 1949.
[10] Barrer and Woodhead, *Trans. Faraday Soc.*, 1948, **44**, 1001.
[11] Eucken, *Z. Elektrochem.*, 1920, **26**, 377.

of the isotherms, are much too small to represent lateral interaction by normal hydrogen-bond formation. Evidently, in favourable cases, the statistical-thermodynamic analysis can give considerable insight into the mechanism of the sorption process and can modify some earlier views.

One of us (W. I. S.) acknowledges the award of a D.S.I.R. Maintenance Grant.

CHEMISTRY DEPARTMENT,
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY,
S. KENSINGTON, LONDON, S.W.1.

[*Received, March 15th*, 1956.]

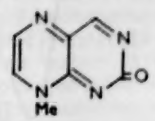
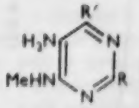
---

643. *Pteridine Derivatives. Part III.*[1] *Bisdihydropurinyls.*

By W. E. FIDLER and H. C. S. WOOD.

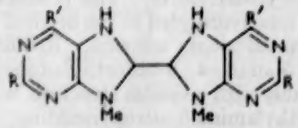
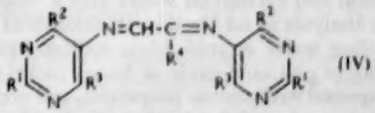
Condensation of 5-amino-2-hydroxy-4-methylaminopyrimidine with glyoxal gave bis-(8 : 9-dihydro-2-hydroxy-9-methylpurin-8-yl) (III; R = OH, R′ = H), and not the expected *N*-alkylpteridone (I). Analogous dihydropurinyls were obtained from glyoxal and other 5-amino-4-methylpyrimidines. Syntheses of several azomethines from glyoxal and 5- or 4-aminopyrimidines are reported. The condensation of 2 : 4 : 5-triamino-6-hydroxypyrimidine with chloral has been re-investigated, and a new synthesis of xanthopterin is described.

IN an attempt to synthesise 2 : 8-dihydro-8-methyl-2-oxopteridine (I), it was observed that condensation of 5-amino-2-hydroxy-4-methylaminopyrimidine (II; R = OH, R′ = H) with glyoxal gave a sparingly soluble, high-melting solid, which had none of the properties

(I)  (II) 

normally associated with *N*-alkylpteridones.[1] This compound, $(C_6H_7ON_4)_n$, was readily soluble in dilute acid or alkali, and was precipitated unchanged from either on neutralisation. Insolubility prevented determination of the molecular weight, and an attempt to prepare a more soluble derivative by methylation was unsuccessful.

Analogous compounds were obtained by condensation of glyoxal with 5-amino-4-methylaminopyrimidine (II; R = R′ = H), 5-amino-4 : 6-bismethylaminopyrimidine (II; R = H, R′ = NHMe), or 5-amino-4-chloro-6-methylaminopyrimidine (II; R = H, R′ = Cl). The chloro-compound was sufficiently soluble in camphor to permit deter-

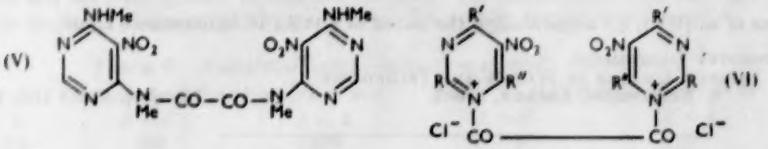
(III)  (IV) 

mination of the molecular weight which indicated that two pyrimidine nuclei had combined with one glyoxal molecule. Comparison of the ultraviolet absorption spectrum of any one of the insoluble compounds with that of the corresponding pyrimidine (Fig. 1) indicated that the pyrimidine nuclei were not linked by a conjugated system. We therefore propose structures (III) for these materials.

We have excluded the alternative azomethine structure (IV; R^3 = NHMe, R^4 = H) by synthesis of an authentic azomethine (IV; $R^1 = R^2 = NMe_2$, $R^3 = R^4$ = H) from glyoxal and 5-amino-2 : 4-bisdimethylaminopyrimidine. This compound was bright red,

[1] Part II, Albert, Brown, and Wood, *J.*, 1956, 2131.

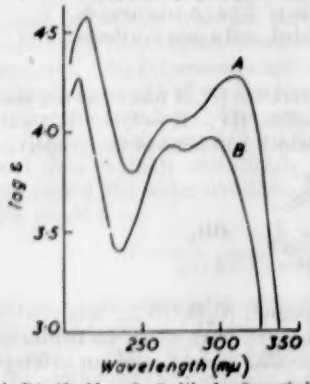
the ultraviolet absorption spectrum (Fig. 2) was distinct from that of the bisdihydropurinyls, and dilute acid readily hydrolyses it to the original pyrimidine, though the bisdihydropurinyls were unaffected by similar treatment. Neither 5-aminopyrimidine



nor 5-amino-4 : 6-dichloropyrimidine reacts with glyoxal under the conditions of the above condensations. This is in agreement with the results of Whittaker,[2] who condensed *p*-nitrobenzaldehyde with 5-aminopyrimidine only under drastic conditions. The presence of at least one electron-releasing group, in addition to the 5-amino-group, appears to be essential for such reactions.

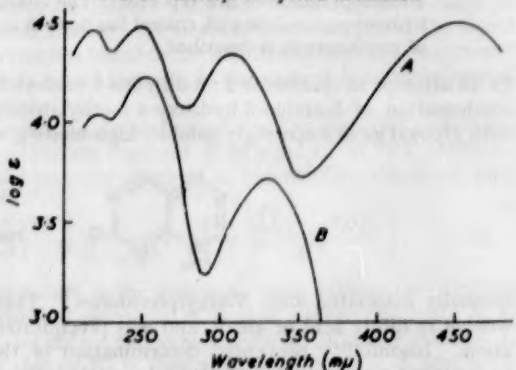
An attempt was made to synthesise a bisdihydropurinyl also by reaction of oxalyl

FIG. 1. *Absorption spectra in ethanol.*



A, Bis-(6-chloro-8 : 9-dihydro-9-methylpurin-8-yl).
B, 5-Amino-6-chloro-4-methylaminopyrimidine.

FIG. 2. *Absorption spectra in ethanol.*



A, Glyoxylidenebis-(5-amino-2 : 4-bisdimethylaminopyrimidine).
B, 5-Amino-2 : 4-bisdimethylaminopyrimidine.

chloride with 4 : 6-bismethylamino-5-nitropyrimidine to give the amide (V), which on reduction and cyclisation would give a bispurin-8-yl derivative. The product, although giving analyses as for the dihydrochloride of (V), was hydrolysed to the original pyrimidine by boiling water or cold dilute sodium hydrogen carbonate solution. Reduction in the presence of platinum oxide or Raney nickel gave 5-amino-4 : 6-bismethylaminopyrimidine. A compound with similar properties, and presumably with a similar structure, was obtained by reaction of oxalyl chloride with 2 : 4-bisdimethylamino-5-nitropyrimidine. We therefore propose the quaternary salt structures (VI; R = H, R′ = R″ = NHMe; and R = R′ = NMe_2, R″ = H, or the 3-isomer) for these products.

Purrmann,[3] in an attempt to synthesise xanthopterin, condensed 2 : 4 : 5-triamino-6-hydroxypyrimidine with chloral, and obtained a strongly fluorescing material, $C_{16}H_{12}O_3N_{10}$, of unknown structure. Repetition of this reaction in acetate buffer gave an apparently identical material, isolated as the crystalline sodium salt. The ultraviolet absorption spectrum of this compound (see Table) resembles that of the azomethine (IV), and differs from those of the bisdihydropurinyls and the azomethines formed by condensation of glyoxal with a 4-aminopyrimidine. We assigned structure (IV; $R^1 = R^3 = NH_2$,

[2] Whittaker, *J.*, 1951, 1565.
[3] Purrmann, *Annalen*, 1941, **548**, 284.

Absorption spectra (in water).

Substance	$\lambda_{max.}$ (mμ)	ε	pH
5-Amino-2-hydroxy-4-methylaminopyrimidine	222; 294	8850; 5280	1
Bis-(8 : 9-dihydro-2-hydroxy-9-methylpurin-8-yl)	233; 330	20,150; 11,000	1
5-Amino-4-methylaminopyrimidine	205; 288	14,300; 8700	7
Bis-(8 : 9-dihydro-9-methylpurin-8-yl)	209; 305	29,500; 15,300	7
5-Amino-4 : 6-bismethylaminopyrimidine	224; 286 [a]	25,100; 10,250	—
Bis-(8 : 9-dihydro-9-methyl-6-methylaminopurin-8-yl)	227; 292 [a]	46,400; 21,400	—
Azomethine (IV; $R^1 = R^3 = NH_2$, $R^2 = R^4 = OH$)	<220; 230; 258; 410	>17,300; 17,340; 15,340; 33,340	13
4-Amino-2 : 6-dihydroxypyrimidine	220; 266	1600; 3580	13
Glyoxylidenebis-(4-amino-2 : 6-dihydroxypyrimidine)	222; 245; 274	15,590; 12,160; 12,800	13
6-Amino-1 : 2 : 3 : 4-tetrahydro-1 : 3-dimethyl-2 : 4-dioxopyrimidine	<220; 266	>2890; 20,950	7
Glyoxylidenebis-(6-amino-1 : 2 : 3 : 4-tetrahydro-1 : 3-dimethyl-2 : 4-dioxopyrimidine)	<220; 240; 274	>16,100; 13,980; 18,980	7

[a] In ethanol.

$R^2 = R^4 = OH$) to this compound. Treatment with dilute mineral acid gives xanthopterin, presumably by cleavage of the azomethine linkage followed by ring closure. Condensation of 2 : 4 : 5-triamino-6-hydroxypyrimidine with chloral in acid solution gives xanthopterin in 36% yield: this compares favourably with other more lengthy syntheses of xanthopterin.[4]

Experimental

Yields of substances that have no definite m. p. refer to the stage when they appeared homogeneous in paper chromatography in butanol–5N-acetic acid (7 : 3) on being viewed in ultraviolet light of wavelengths 254 and 365 mμ.

Bis-(8 : 9-dihydro-2-hydroxy-9-methylpurin-8-yl).—5-Amino-2-hydroxy-4-methylaminopyrimidine [5] (2·67 g.) was dissolved in water (55 c.c.) at 50°, and glyoxal (2·67 g. of 50% aqueous solution) in water (27 c.c.) was added. A bright yellow precipitate was formed almost immediately, and this rapidly changed colour to buff. The mixture was heated at 50° for 15 min., and the solid (2·3 g., 80%) was collected, washed with warm water, and dried. A sample was purified by dissolution in dilute hydrochloric acid, filtering, and addition of dilute sodium hydroxide solution to pH 9—10; *bis-(8 : 9-dihydro-2-hydroxy-9-methylpurin-8-yl)* was precipitated as pale yellow needles, m. p. >300° (Found: C, 47·9; H, 5·0; N, 36·8. $C_{12}H_{14}O_2N_8$ requires C, 47·7; H, 4·7; N, 37·1%). The bisdihydropurinyl is soluble in dilute alkali; it could not be methylated by using diazomethane, methyl sulphate and alkali, or methyl iodide and potassium carbonate.

Bis-(8 : 9-dihydro-9-methylpurin-8-yl).—5-Amino-4-methylaminopyrimidine [6] (0·69 g.) was dissolved in boiling water (3 c.c.), and a solution of solid polyglyoxal (0·161 g.) in boiling water (4 c.c.) was added. The solution was refluxed for 1 hr., and chilled overnight. The solid (0·58 g., 80%) was collected and recrystallised from ethanol–water, to give the *bisdihydropurinyl* as colourless needles, m. p. *ca.* 270° (decomp.) (Found: C, 53·2; H, 5·0; N, 41·2. $C_{12}H_{14}N_8$ requires C, 53·3; H, 5·2; N, 41·5%).

Bis-(6-chloro-8 : 9-dihydro-9-methylpurin-8-yl).—5-Amino-6-chloro-4-methylaminopyrimidine [6] was condensed with polyglyoxal as above to give the *bischlorodihydropurinyl* as colourless needles (65%), m. p. *ca.* 270° (decomp.) [Found: C, 42·5; H, 3·8; N, 32·9; Cl, 20·8%; *M* (Rast), 320, 340. $C_{12}H_{12}N_8Cl_2$ requires C, 42·5; H, 3·6; N, 33·1; Cl, 20·9%; *M*, 339].

5-Amino-4 : 6-bismethylaminopyrimidine.—4 : 6-Bismethylamino-5-nitropyrimidine [6] (0·45 g.) in ethanol (50 c.c.) was hydrogenated over Raney nickel at room temperature and pressure. The catalyst was filtered off and washed with hot ethanol. The combined filtrates were taken to dryness *in vacuo*, and the residue sublimed at 110° (bath)/0·005 mm., to give *5-amino-4 : 6-bismethylaminopyrimidine*, m. p. 150° (decomp.) (Found: C, 47·3; H, 7·2; N, 45·5. $C_6H_{11}N_5$ requires C, 47·0; H, 7·2; N, 45·7%).

Bis-(8 : 9-dihydro-9-methyl-6-methylaminopurin-8-yl).—(*a*) To the above crude ethanolic solution of 5-amino-4 : 6-bismethylaminopyrimidine was added polyglyoxal (0·075 g.) in water

[4] Albert and Wood, *J. Appl. Chem.*, 1952, **2**, 591; Korte and Fuchs, *Chem. Ber.*, 1953, **86**, 114.
[5] Brown, *J. Appl. Chem.*, 1955, **5**, 358.
[6] *Idem, ibid.*, 1954, **4**, 72.

(10 c.c.), and the mixture was heated on the steam-bath for 10 min. The solution was concentrated *in vacuo* to *ca.* 5 c.c., and chilled overnight to give the *bisdihydropurinyl* as colourless needles (from ethanol), m. p. 260° (decomp.) (Found: C, 50·9; H, 5·5; N, 43·2. $C_{14}H_{20}N_{10}$ requires C, 51·2; H, 6·1; N, 42·7%).

(*b*) Bis-(6-chloro-8 : 9-dihydro-9-methylpurin-8-yl) (0·05 g.) and 33% ethanolic methylamine (1 c.c.) were heated in a sealed tube for 5 hr., at 125°, then cooled. The solid, recrystallised from ethanol, gave the bisdihydropurinyl, m. p. 258° (decomp.).

2 : 4-*Bisdimethylamino-5-nitropyrimidine.*—2 : 4-Dichloro-5-nitropyrimidine[7] (1 g.) was suspended in ethanol (20 c.c.), and 33% ethanolic dimethylamine (3 c.c.) was added dropwise. The solution was stirred for 30 min., then filtered, and the filtrate was taken to dryness. The residue was sublimed and recrystallised from light petroleum (b. p. 60—80°), to give 2 : 4-*bisdimethylamino-5-nitropyrimidine* (1 g., 92%) as yellow needles, m. p. 88—92° (Found: C, 45·7; H, 5·5; N, 33·7. $C_6H_{13}O_2N_5$ requires C, 45·5; H, 6·2; N, 33·2%).

*5-Amino-*2 : 4-*bisdimethylaminopyrimidine.*—The above nitro-compound was hydrogenated over Raney nickel in the usual way, to give *5-amino-*2 : 4-*bisdimethylaminopyrimidine* as white needles, m. p. 92—96°, after sublimination at 90° (bath)/0·01 mm. (Found: C, 53·7; H, 7·9; $C_8H_{15}N_5$ requires C, 53·0; H, 8·3%). The mixed m. p. with 5-nitro-derivative was 66—84°.

*Azomethine of Glyoxal and 5-Amino-*2 : 4-*bisdimethylaminopyrimidine.*—5-Amino-2 : 4-bisdimethylaminopyrimidine (0·2 g.) was dissolved in a mixture of hot water (10 c.c.) and ethanol (3 c.c.), and a solution of polyglyoxal (0·038 g.) in hot water (5 c.c.) added, yielding a precipitate at once. The mixture was heated on the steam-bath for 2 min., and cooled, giving *glyoxylidenebis-*(*5-amino-*2 : 4-*bisdimethylaminopyrimidine*) as bright red needles (from aqueous ethanol), m. p. 195—199° (Found: C, 56·7; H, 6·7; N, 36·7. $C_{18}H_{32}N_{10}$ requires C, 56·2; H, 7·3; N, 36·5%). The azomethine was immediately hydrolysed by cold N-hydrochloric acid.

5-Aminopyrimidine.—Hydrogenation of 5-amino-4 : 6-dichloropyrimidine, in the presence of magnesium oxide and palladium–charcoal, gave 5-aminopyrimidine, m. p. 169—171°. Whittaker[8] obtained this compound in a similar manner from 5-amino-2 : 4-dichloropyrimidine.

Neither 5-aminopyrimidine nor 5-amino-4 : 6-dichloropyrimidine[6] reacted with glyoxal when refluxed for several hours in water or ethanol.

*Oxalylbis-*1-(4 : 6-*bismethylamino-5-nitropyrimidinium Chloride*).—To a solution of 4 : 6-bismethylamino-5-nitropyrimidine (0·5 g.) in dry boiling benzene (200 c.c.) was added a solution of redistilled oxalyl chloride (0·11 c.c.) in dry benzene (10 c.c.). The solution was refluxed for 30 min., during which a precipitate was gradually formed. The pale yellow *quaternary salt* (0·43 g., 65%), collected and dried *in vacuo*, had m. p. 255° (decomp.) (Found: C, 34·5; H, 4·5; N, 28·5; Cl, 14·7. $C_{14}H_{18}O_6N_{10}Cl_2$ requires C, 34·1; H, 3·7; N, 28·4; Cl, 14·4%).

4 : 6-Bismethylamino-5-nitropyrimidine did not react when fused with oxalic acid for 30 min. at 160°.

*Oxalylbis-*1(or 3)-(2 : 4-*bisdimethylamino-5-nitropyrimidinium Chloride*).—2 : 4-Bisdimethylamino-5-nitropyrimidine with oxalyl chloride in ether gave the *pyrimidinium salt* as yellow crystals, m. p. 154—158° (Found: C, 39·2; H, 5·0; N, 25·2. $C_{18}H_{26}O_6N_{10}Cl_2$ requires C, 39·3; H, 4·8; N, 25·5%).

Condensation of 2 : 4 : 5-*Triamino-6-hydroxypyrimidine with Chloral.*—(*a*) Triaminohydroxypyrimidine sulphate monohydrate (2 g.) and crystalline sodium acetate (6 g.) were dissolved in water (100 c.c.) containing sodium dithionite (50 mg.). Chloral hydrate (1·4 g.) was added and the mixture kept at room temperature for 2 days. The yellow precipitate (1·3 g.) was collected, washed with water, and dissolved in boiling 2N-sodium hydroxide (25 c.c.). On cooling, *sodium* N-(2 : 4-*diamino-6-hydroxypyrimidin-5-yl*)-α-(2 : 4-*diamino-6-hydroxypyrimidin-5-ylimino*)*acetimidoate* (IV; $R^1 = R^2 = NH_2$, $R^3 = OH$; $R^4 = ONa$) crystallised as yellow needles (Found: C, 35·3; H, 3·4; N, 40·5. $C_{10}H_{11}O_3N_{10}Na$ requires C, 35·1; H, 3·2; N, 40·9%).

This azomethine (0·15 g.) was heated in 2N-hydrochloric acid (10 c.c.) on the steam-bath for 30 min. Ammonia was added to pH 4·8, and after refrigeration crude xanthopterin (0·08 g.) was collected and purified as below, to give material with an identical absorption spectrum.

(*b*) Triaminohydroxypyrimidine sulphate monohydrate (2 g.) was dissolved in a mixture of concentrated sulphuric acid (24 c.c.) and water (4 c.c.). Chloral hydrate (1·4 g.) was added, and the mixture was heated on the steam-bath for 1 hr., whereafter evolution of hydrogen chloride had largely ceased. The cooled solution was poured on cracked ice (100 g.), and the pH taken to 4·8 with ammonia. After refrigeration overnight, the yellow-brown precipitate was collected, washed successively with water, ethanol, and ether, and dried *in vacuo*. The

[7] Brown, *J. Appl. Chem.*, 1952, **2**, 239

xanthopterin (0·55 g., 36%) was purified *via* the crystalline barium salt as described by Korte and Fuchs.[4] Light absorption in water (pH 13): $\lambda_{max.}$ 255 and 392 mμ (log ε 4·26 and 3·84 respectively).

Azomethine from Glyoxal and 4-Amino-2 : 6-dihydroxypyrimidine.—Polyglyoxal (0·23 g.) in warm water (20 c.c.) was added to a solution of 4-amino-2 : 6-dihydroxypyrimidine[5] (1 g.) in boiling water (200 c.c.), a precipitate being formed almost immediately. The mixture was refluxed for 1 hr., and the solid (0·35 g.) was collected at 95—100°. This material was purified by dissolving it in hot 2N-sodium carbonate (20 c.c.), to give a red solution from which *glyoxylidenebis-(4-amino-2 : 6-dihydroxypyrimidine)*, m. p. >360°, was precipitated with dilute hydrochloric acid (Found: C, 43·7; H, 2·9; N, 30·0. $C_{10}H_8O_4N_6$ requires C, 43·5; H, 2·9; N, 30·4%).

Azomethine from Glyoxal and 6-Amino-1 : 2 : 3 : 4-tetrahydro-1 : 3-dimethyl-2 : 4-dioxopyrimidine.—Similar condensation of glyoxal with the pyrimid-dione[5] gave *glyoxylidenebis-(6-amino-1 : 2 : 3 : 4-tetrahydro-1 : 3-dimethyl-2 : 4-dioxopyrimidine)* as colourless needles (68%) (from water), m. p. >300° (Found: C, 50·6; H, 4·4; N, 25·3. $C_{14}H_{16}O_4N_6$ requires C, 50·6; H, 4·9; N, 25·3%).

THE ROYAL TECHNICAL COLLEGE, GLASGOW. [*Received, March 29th*, 1956.]

[4] Ruttink, *Rec. Trav. chim.*, 1946, **65**, 764.
[5] Speer and Raymond, *J. Amer. Chem. Soc.*, 1953, **75**, 114.

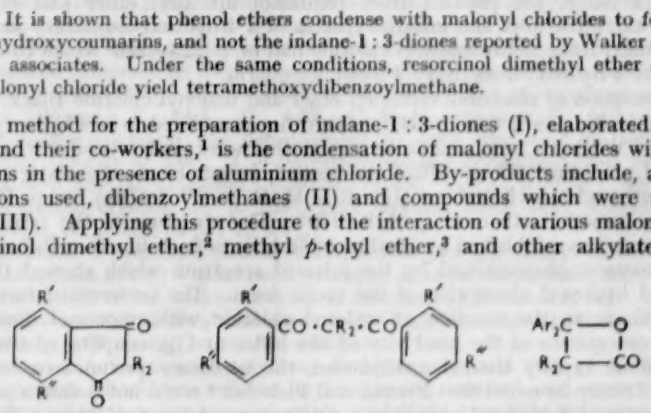
---

644. *A New Synthesis of 4-Hydroxycoumarins.*

By J. F. GARDEN, N. F. HAYES, and R. H. THOMSON.

It is shown that phenol ethers condense with malonyl chlorides to form 4-hydroxycoumarins, and not the indane-1 : 3-diones reported by Walker and his associates. Under the same conditions, resorcinol dimethyl ether and malonyl chloride yield tetramethoxydibenzoylmethane.

A GENERAL method for the preparation of indane-1 : 3-diones (I), elaborated by Freund, Fleischer, and their co-workers,[1] is the condensation of malonyl chlorides with aromatic hydrocarbons in the presence of aluminium chloride. By-products include, according to the conditions used, dibenzoylmethanes (II) and compounds which were regarded as β-lactones (III). Applying this procedure to the interaction of various malonyl chlorides with resorcinol dimethyl ether,[2] methyl *p*-tolyl ether,[3] and other alkylated phenols,[4]



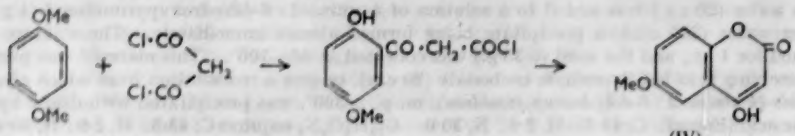
(I) (II) (III)

Walker and his associates prepared over thirty compounds which were regarded as indanediones on the basis of their analyses and molecular weights, coupled with the fact that they did not behave as lactones. Re-investigation of part of this work in connection with an attempted synthesis of 4 : 7-dimethoxyindanedione, has now shown that these compounds are actually coumarins.

Walker *et al.*[3] could obtain no useful result from condensations with quinol dimethyl ether but in our hands reaction with malonyl chloride (or bromide) readily gave a product (A), $C_{10}H_8O_4$, corresponding to a hydroxymethoxyindanedione (I; R = H, R′ = OH, R″ = OMe). (Partial demethylation had previously been observed in reactions with

[1] Freund and Fleischer, *Annalen*, 1910, **373**, 291; 1913, **399**, 182; 1914, **402**, 51; 1916, **411**, 14; 1918, **414**, 1; 1921, **422**, 231.
[2] Black, Shaw, and Walker, *J.*, 1931, 272.
[3] Walker, Suthers, Roe, and Shaw, *J.*, 1931, 514.
[4] Robinson, Suthers, and Walker, *Biochem. J.*, 1932, **26**, 1890.

resorcinol dimethyl ether.[3]) However, its infrared spectrum showed that it could not be an indanedione and further investigation established the coumarin structure (IV) which was confirmed by an alternative synthesis.[5] The formation of coumarins by this reaction,



(IV)

which must include partial demethylation as shown above, was previously observed by Freund and Fleischer [6] who found that diethylmalonyl chloride and quinol dimethyl ether gave the expected indanediones (I; R = Et, R′ = R″ = OMe, and R = Et, R′ = OH, R″ = OMe) but the major product was a coumarin derivative. Black, Shaw, and Walker [3] refer to this work but overlooked that point. Two homologues of the coumarin (IV) were obtained in low yield by interaction of methyl- and ethyl-malonyl chlorides respectively with quinol dimethyl ether.

We therefore repeated one of the experiments of Walker *et al.* in each group, *i.e.*, one with resorcinol dimethyl ether and one with methyl *p*-tolyl ether. The product from methyl *p*-tolyl ether and malonyl chloride had the properties described. Its ultraviolet absorption curve is almost identical with that of 4-hydroxycoumarin, and an alternative synthesis by Boyd and Robertson's method established the structure 4-hydroxy-6-methylcoumarin. Similarly, the product from resorcinol dimethyl ether and ethylmalonyl chloride had the ultraviolet and infrared spectra of a 4-hydroxycoumarin; and the compound [2] obtained from methylmalonyl chloride had m. p. 225—226° which corresponds to that (227°) of 4-hydroxy-7-methoxy-3-methylcoumarin.[7]

By condensation of resorcinol dimethyl ether and malonyl chloride Black, Shaw, and Walker [3] obtained a product, m. p. 217°, which they considered to be a hydroxy-methoxyindanedione. We have been unable to repeat this work and several variations of the experimental procedure did not affect the result. In our hands the major product was di-(2 : 4-dimethoxybenzoyl)methane (II; R = H, R′ = R″ = OMe), m. p. 133°, accompanied by a trimethyl ether, m. p. 118—120°. The structure of the tetramethoxydibenzoylmethane was established by alkaline hydrolysis to 2 : 4-dimethoxybenzoic acid and 2 : 4-dimethoxyacetophenone and by the infrared spectrum which showed the chelated carbonyl and hydroxyl absorption of the enolic form. The preferential formation of a dibenzoylmethane in the reaction of malonyl chloride with resorcinol dimethyl ether must be a consequence of the reactivity of the latter at $C_{(4)}$, coupling of two molecules proceeding more rapidly than demethylation, the necessary preliminary for coumarin formation. It may be noted that Freund and Fleischer [6] could not isolate a pure product from the reaction of diethylmalonyl chloride with resorcinol dimethyl ether. The formation of an indanedione from this ether is highly improbable as it involves cyclisation at $C_{(5)}$, a most unreactive position [cf. cyclisation of γ-(2 : 4-dimethoxyphenyl)butyric acid, which yields only *ca.* 5% of the corresponding tetralone [8]].

The ultraviolet absorption maxima of the 4-hydroxycoumarins are listed in the Table. The absorption curve of 4 : 6-dimethoxycoumarin is markedly different from that of 4 : 6-dihydroxycoumarin and the other 4-hydroxycoumarins; not only are the peaks displaced but they are separated by a trough of much lower intensity. This implies that the 4-hydroxycoumarins exist in the keto-form in ethanol solution (but cf. ref. 9). The introduction of an alkyl group has the usual effect of shifting the absorption to longer wavelengths, but a 7-methoxyl group produces a marked change in the absorption pattern,

[5] Badcock, Dean, Robertson, and Whalley, *J.*, 1950, 903.
[6] Freund and Fleischer, *Annalen*, 1915, **409**, 268.
[7] Boyd and Robertson, *J.*, 1948, 174.
[8] Halpern, *Helv. Chim. Acta*, 1952, **35**, 930 (footnote); Davies, King, and Roberts, *J.*, 1955, 2782.
[9] Chmielewska and Ciecierska, *Przemysl Chem.*, 1952, **31**, 253.

Ultraviolet absorption maxima (mμ) *of 4-hydroxycoumarins.*

Coumarin	Ethanol solution					
	$\lambda_{max.}$	log ε	$\lambda_{max.}$	log ε	$\lambda_{max.}$	log ε
4-Hydroxy	—	—	290	4·10	301	4·08
4-Hydroxy-6-methoxy	—	—	300	4·17	314	4·05
4 : 6-Dihydroxy	—	—	300	4·135	315	3·94
4 : 6-Dimethoxy	—	—	270	4·07	327 (max.)	3·73
3-Ethyl-4-hydroxy-6-methoxy	—	—	307	4·12	322 (max.)	4·12
4-Hydroxy-6-methoxy-3-methyl	—	—	306	4·17	320 (max.)	4·14
4-Hydroxy-6-methyl	—	—	293	4·12	304	4·07
4-Hydroxy-7-methoxy	245	4·07	304	4·23	—	—
3-Ethyl-4-hydroxy-7-methoxy	249	4·03	314	4·28	—	—
4-Hydroxy-7-methoxy-3-methyl	247	4·05	313	4·25	—	—

consistent with its position *para* to the unsaturated side chain. The infrared spectra of these compounds will be reported in a separate communication.

Experimental

4-Hydroxy-6-methoxycoumarin.—(*a*) Finely powdered anhydrous aluminium chloride (13·5 g.) was added, in portions, during 20 min., to a mixture of quinol dimethyl ether (7 g.) and malonyl chloride (7 g.) in dry carbon disulphide (50 ml.). The mixture was set aside for 24 hr. and then refluxed in a water-bath for 2 hr. After removal of the solvent, the complex was decomposed with water (100 ml.) and concentrated hydrochloric acid (50 ml.), warmed to 80°, and cooled, and the precipitate collected. The product, after dissolution in 10% aqueous sodium hydroxide (100 ml.) and reprecipitation with dilute hydrochloric acid, separated from aqueous acetic acid as needles, m. p. 270° (3 g., 30%) (Found: C, 62·35; H, 4·2. Calc. for $C_{10}H_8O_4$: C, 62·5; H, 4·35%). Refluxing the hydroxymethoxycoumarin in methyl sulphate–acetone–potassium carbonate for 2 hr. gave the *dimethyl ether* as needles, m. p. 138° [from light petroleum (b. p. 100—120°)], also obtained by treatment of 4 : 6-dihydroxycoumarin with diazomethane (Found: C, 64·2; H, 4·55. $C_{11}H_{10}O_4$ requires C, 64·1; H, 4·85%). 4-Hydroxy-6-methoxycoumarin was demethylated by brief treatment in fused aluminium chloride–sodium chloride at 180°. *4 : 6-Dihydroxycoumarin* crystallised from aqueous acetic acid in plates, m. p. 290° (45%) (Found: C, 60·55; H, 3·6. $C_9H_6O_4$ requires C, 60·7; H, 3·4%). The *diacetate* formed crystals, m. p. 226°, from aqueous acetic acid (Found: C, 59·55; H, 3·6. $C_{13}H_{10}O_6$ requires C, 59·55; H, 3·8%).

(*b*) A mixture of 2-hydroxy-5-methoxyacetophenone (0·9 g.), diethyl carbonate (30 ml.), and pulverised sodium (0·9 g.) was set aside overnight at room temperature, then warmed on a steam-bath for 1½ hr., cooled, and worked up as described by Badcock *et al.*[5] The coumarin formed needles, m. p. 270° (from glacial acetic acid) (1 g.), identical with those obtained in (*a*) above. The m. p. 170° quoted in ref. 5 is a misprint.

Hydrolyses.—(*a*) A solution of 4-hydroxy-6-methoxycoumarin (0·5 g.) in 30% aqueous potassium hydroxide (50 ml.) was refluxed for 2 hr., cooled, acidified, and extracted with ether, to give 2-hydroxy-5-methoxybenzoic acid which crystallised from light petroleum (b. p. 100—120°) in needles, m. p. and mixed m. p. 144° (35%). Methylation gave 2 : 5-dimethoxybenzoic acid, m. p. and mixed m. p. 80°. Concentration of the mother-liquor after separation of the acid, m. p. 144°, yielded 2-hydroxy-5-methoxyacetophenone as yellow needles, m. p. and mixed m. p. 52° (60%); demethylation with hydrobromic acid gave 2 : 5-dihydroxyacetophenone m. p. and mixed m. p. 204°.

(*b*) By the above procedure, 4 : 6-dihydroxycoumarin gave 2 : 5-dihydroxyacetophenone and 2 : 5-dihydroxybenzoic acid, needles, m. p. 206° (from ethyl acetate–light petroleum). This acid was also obtained by demethylation of its mono- and di-methyl ether (above) using (i) aluminium chloride–sodium chloride and (ii) hydrobromic acid.

(*c*) In the same way hydrolysis of 4 : 6-dimethoxycoumarin (0·3 g.) yielded 2-hydroxy-5-methoxyacetophenone (0·18 g.) and 2-hydroxy-5-methoxybenzoic acid (75 mg.).

4-Hydroxy-6-methoxy-3-methylcoumarin.—This coumarin, prepared from methylmalonyl chloride and quinol dimethyl ether, crystallised from aqueous methanol as plates, m. p. 222° (4%) (Found: C, 63·75; H, 4·65. $C_{11}H_{10}O_4$ requires C, 64·0; H, 4·85%).

3-Ethyl-4-hydroxy-6-methoxycoumarin.—This was obtained from quinol dimethyl ether and ethylmalonyl chloride as plates, m. p. 187° (8%) (Found: C, 65·15; H, 5·45. $C_{12}H_{12}O_4$

requires C, 65·4; H, 5·45%). The *acetate* formed needles (from aqueous acetic acid), m. p. 78° (Found: C, 63·9; H, 5·35. $C_{14}H_{14}O_5$ requires C, 64·1; H, 5·35%).

3-Ethyl-4-hydroxy-7-methoxycoumarin.—This was obtained from resorcinol dimethyl ether and ethylmalonyl chloride by following the procedure of Black, Shaw, and Walker,[3] and formed fawn-coloured cubes, m. p. 192° from methanol (Found: C, 65·3; H, 5·4; OMe, 13·0. $C_{12}H_{12}O_4$ requires C, 65·5; H, 5·5; OMe, 14·1%). The *acetate* crystallised from water in needles, m. p. 99° (Found: C, 64·4; H, 5·3. $C_{14}H_{14}O_5$ requires C, 64·15; H, 5·4%). The *methyl ether* formed needles, m. p. 70°, from methanol (Found: C, 66·7; H, 6·0. $C_{13}H_{14}O_4$ requires C, 66·7; H, 6·0%).

4-Hydroxy-6-methylcoumarin.—(*a*) Methyl *p*-tolyl ether and malonyl chloride in nitrobenzene were treated with anhydrous aluminium chloride according to Walker *et al.*[3] The coumarin crystallised from methanol in needles, m. p. 258°. The acetate formed prismatic needles, m. p. 149°, from methanol.

(*b*) 2-Acetyl-4-methylphenol (1·0 g.), ethyl carbonate (30 ml.), and pulverised sodium (0·75 g.) were heated on a steam-bath for ¾ hr. and worked up as before. The coumarin formed needles m. p. 258°, identical with those obtained in (*a*).

Di-(2 : 4-dimethoxybenzoyl)methane.—Anhydrous aluminium chloride (13·5 g.) was added gradually to a stirred solution of resorcinol dimethyl ether (7 g.) and malonyl chloride (7 g.) in dry nitrobenzene (60 ml.), the temperature being allowed to rise. The mixture was then warmed to 60—65° for 30 min., cooled, and treated with ice and hydrochloric acid. After removal of the solvent in steam, the residue was repeatedly extracted with ether, and the extract then shaken with 5% aqueous sodium hydroxide. Evaporation of the dried ether solution left crystalline material (0·6 g.) which separated from methanol in lemon-yellow needles, m. p. 133° (Found: C, 66·0; H, 6·0; OMe, 34·8. $C_{19}H_{20}O_6$ requires C, 66·2; H, 6·25; 4OMe, 36·0%). Light absorption: max. at 206, 245, 273, 308, and 373 mμ (log ε 4·5, 4·09, 4·05, 4·08, and 4·43 respectively) in EtOH. The carbonyl frequency lay at 1605 cm.$^{-1}$, diffuse hydroxyl absorption from 2800 to below 2000 cm.$^{-1}$ in $CHCl_3$. The *product* was soluble in warm aqueous sodium hydroxide and gave a green colour with ferric chloride. Acidification of the sodium hydroxide washings precipitated an oil (2·7 g.) which, after crystallisation from methanol, was chromatographed in chloroform on alumina. Two yellow bands appeared. From the lower one a further small quantity of the tetramethoxy-compound, m. p. 130—131°, was obtained whilst the upper zone gave the *trimethyl ether* which separated from methanol in yellow needles, m. p. 118—120° [Found: C, 64·65; H, 5·7; OMe, 26·7. $C_{15}H_9O_3(OMe)_3$ requires C, 64·45; H, 5·5; 3OMe, 28·1%]. Methylation of the latter with methyl sulphate–acetone–potassium carbonate gave the tetramethoxy-compound as lemon-yellow needles, m. p. and mixed m. p. 133°.

Hydrolysis of Di-(2 : 4-dimethoxybenzoyl)methane.—The tetramethyl ether (1 g.) was refluxed for 2 hr. with 15% aqueous potassium hydroxide (20 ml.). On cooling, the oil which had separated solidified and was collected. Crystallisation from aqueous methanol gave prisms (0·45 g.), m. p. 38—40° alone or mixed with 2 : 4-dimethoxyacetophenone. Acidification of the alkaline filtrate deposited needles (0·43 g.) which on recrystallisation from water had m. p. 108° alone or mixed with 2 : 4-dimethoxybenzoic acid. A similar hydrolysis of the trimethoxydibenzoylmethane also gave 2 : 4-dimethoxyacetophenone together with acidic material, converted by methylation into 2 : 4-dimethoxybenzoic acid.

One of us (N. F. H.) is grateful to the Department of Scientific and Industrial Research for a Maintenance Allowance, and another (J. F. G.) to the Banffshire Education Committee for a Trust Bursary. We also thank Dr. V. C. Farmer for the infrared data and Dr. W. B. Whalley for several coumarin samples.

The University, Old Aberdeen, Scotland. [*Received, April 23rd,* 1956.]

645. *The Formation of Phenyl Radicals from Tetraphenyl-lead.*

By J. E. Spice and W. Twist.

Tetraphenyl-lead reacts with silver nitrate in benzene–ethanol at about 60° to give metallic silver, triphenyl-lead nitrate, and phenyl radicals. Investigation of the products of the reaction shows that most of the phenyl radicals remove hydrogen from the ethanol, while a small proportion dimerise or react with benzene, to form diphenyl. The reaction is bimolecular, with a a temperature coefficient of ~18,500 cal./mole and a temperature-independent factor of $\sim 10^{16}$ l. mole^{-1} sec.$^{-1}$.

The object of the present work was to investigate the reaction between silver nitrate and tetraphenyl-lead, as a means of producing phenylsilver and hence free phenyl radicals in solution. The preparation of phenylsilver has several times been reported, but the products do not seem to have been well characterised. Thus, yellow solids of composition $AgPh_2,AgNO_3$ have been obtained by the action of excess of silver nitrate in ethanolic solution on triphenylbismuth [1] and on ethyltriphenyl-lead.[2] These solids were said to decompose, when warmed, into silver nitrate, silver, and diphenyl, and to be fairly soluble in benzene. Products claimed to be essentially phenylsilver were obtained by Reich [3] and by Krause and Wendt [4] by the action of phenylmagnesium bromide on silver chloride in ethereal suspension at a low temperature, but were unstable even at room temperature, and barely soluble in benzene. Gilman and Straley [5] used the same method and, without isolating the product, showed that the reaction mixture gave phenyl radicals, which reacted either with each other or with added reagents. Gilman and Woods [6] caused silver nitrate to react with tetraphenyl-lead in ethanolic suspension, and obtained metallic silver and a good yield of diphenyl.

The reaction between lead tetra-alkyls and silver nitrate in ethanolic solution has been investigated by Semerano and Riccoboni [7] and by Bawn and Whitby.[8] They have shown that the silver alkyl is first formed by a rapid electron-transfer, $PbR_4 + Ag^+ \longrightarrow AgR + PbR_3^+$, and later decomposes slowly by a unimolecular mechanism to give free alkyl radicals and metallic silver. These reactions occur below room temperature and provide a convenient source of free alkyl radicals in solution. Glockling [9] recently described similar experiments with *iso*but-1-enyltriethyl-lead. When lead tetra-alkyls react with cupric nitrate, however, cupric alkyls cannot be isolated [8] but free radicals are produced, presumably by the reaction: $Cu^{++} + PbR_4 \longrightarrow Cu^+ + PbR_3^+ + R\cdot$.

In the present work, the reaction between silver nitrate and tetraphenyl-lead in dilute solution was analogous to that between lead tetra-alkyls and cupric nitrate, in that metallic silver and phenyl radicals are produced, although phenylsilver cannot be separated from the reaction mixture.

Experimental

"AnalaR" silver nitrate was used without further purification. Tetraphenyl-lead was prepared by the action of lead chloride on phenylmagnesium bromide [10] and purified by recrystallisation from benzene. Ethyl alcohol and benzene were dried in the usual way; in addition, the alcohol was refluxed with potassium hydroxide and silver nitrate and then distilled, in order to remove any acetaldehyde.

No single common solvent for silver nitrate and tetraphenyl-lead could be found, and it was therefore necessary to use a mixture of ethyl alcohol and benzene. Because of the low solubility

[1] Challenger *et al.*, *J.*, 1921, **119**, 817; 1922, **121**, 104; 1934, 405.
[2] Krause and Schmidt, *Ber.*, 1919, **52**, 2150.
[3] Reich, *Compt. rend.*, 1923, **177**, 322.
[4] Krause and Wendt, *Ber.*, 1923, **56**, 2064.
[5] Gilman and Straley, *Rec. Trav. chim.*, 1936, **55**, 821.
[6] Gilman and Woods, *J. Amer. Chem. Soc.*, 1943, **65**, 435.
[7] Semerano and Riccoboni, *Ber.*, 1941, **74**, 1089, 1297; *Z. phys. Chem.*, 1941, **189**, *A*, 203.
[8] Bawn and Whitby, *Discuss. Faraday Soc.*, 1947, **2**, 228.
[9] Glockling, *J.*, 1955, 716.
[10] Gilman, *J. Amer. Chem. Soc.*, 1927, **49**, 2316.

of tetraphenyl-lead, the maximum concentration of this compound was about 0·015M. For the kinetic measurements, 25-ml. portions of an ethanolic solution of silver nitrate and of a benzene solution of tetraphenyl-lead were left to attain the temperature of a thermostat (60° unless otherwise stated). The solutions were then mixed rapidly in stoppered tubes, which were analysed after various times in the thermostat. Rapid filtration through a sintered-glass filter was followed by dissolution of the metallic silver in moderately concentrated nitric acid, and its determination by Volhard's procedure. The reaction was complete in about 24 hr. at 60°.

For the investigation of the products the mixed solutions were usually refluxed for at least 24 hr. A variation of Pozzi-Escot's steam-distillation technique [11] was developed into a moderately accurate procedure for the estimation of quantities of diphenyl of the order of 20 mg., present in about 400 ml. of solution. (The impossibility of using high concentrations, and the difficulty of handling large volumes, meant that larger quantities of diphenyl could not be expected.) The solution containing the diphenyl and other products was concentrated to 2—3 ml. by distillation, and the last traces of solvent were removed under reduced pressure. The residue was extracted three times with 3—4 ml. portions of ether, and the combined extracts were transferred to a small vessel for steam-distillation. The ether was first removed by evaporation in a stream of air, leaving diphenyl together with a small quantity of the lead-containing product. The diphenyl was now transferred by steam-distillation direct to a sintered-glass filter; after being washed with cold water, it was washed through, in ethereal solution, into another small vessel. The ether was allowed to evaporate in a stream of air, and the vessel dried to constant weight in a desiccator. In blank experiments with known weights of diphenyl, there was an average recovery of about 85%.

Products of the Reaction.—When solutions of silver nitrate and tetraphenyl-lead were mixed a yellow colour developed, which after a few minutes had deepened to black through orange and purple. This succession of colours was doubtless due to the increasing size of colloidal particles of silver. Within ½ hr., a silver mirror was usually visible on the walls of the tube, and thereafter the amount of silver continued to increase.

Phenylsilver. By analogy with the reaction between silver nitrate and tetramethyl-lead [8] the present reaction might have been expected to give phenylsilver by a rapid electron-transfer process, followed by a slow decomposition of the phenylsilver. According to previous workers, phenylsilver is quite stable at room temperature, and not very soluble in benzene. It should therefore have been possible to precipitate it by addition of excess of ethanol. However, a white precipitate which was slowly formed on addition of excess of ethanol to the reaction mixture proved to be unchanged tetraphenyl-lead. Nearly all this was, in fact, precipitated in this way, whether the ethanol was added as soon as the solutions of the reactants had been mixed, or after an interval. Moreover, when the freshly mixed solutions were evaporated under reduced pressure, the solid residue consisted almost entirely of unchanged silver nitrate and tetraphenyl-lead. Attempts were also made to prepare solid phenylsilver, according to directions given in the literature.[3,4] The products, however, were all insoluble in alcohol–benzene. These facts exclude the formation of phenylsilver by a rapid reaction, and indicate that the reaction may be either

$$Ag^+NO_3^- + PbPh_4 \xrightarrow{\text{Slow}} PbPh_3{}^+NO_3^- + Ag + C_6H_5^{\bullet} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

or

$$\left.\begin{aligned} Ag^+NO_3^- + PbPh_4 &\xrightarrow{\text{Slow}} PbPh_3{}^+NO_3^- + AgPh \\ AgPh &\xrightarrow{\text{Fast}} Ag + C_6H_5^{\bullet} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The two-stage scheme (2) is mechanistically more probable than the reaction (1). However, the relative merits of these alternatives will not be discussed further, since kinetic measurements cannot distinguish between them.

The lead-containing product. This was isolated by evaporating the mixed solutions when the reaction was complete, and extracting unchanged tetraphenyl-lead with benzene. When the concentration of the mixed solution was 0·005M with respect to each reactant (as was always the case in the investigations of the products of the reaction, unless otherwise stated) the unchanged tetraphenyl-lead amounted, on the average, to about 30% of the total weight originally present. From the residue left after extraction of unchanged tetraphenyl-lead a crystalline compound was isolated, containing lead and the nitrate group in equimolecular proportions. Triphenyl-lead nitrate was made by several methods, such as the reaction between silver nitrate and

[11] Pozzi-Escot, *Bull. Soc. chim.*, 1904, **31**, 932.

triphenyl-lead bromide,[12] and it and the reaction product were shown by mixed m. p. determinations to be identical. In twelve experiments, the yield of triphenyl-lead nitrate varied between 65% and 75% of that to be expected on the basis of reaction (1) or (2) going to completion.

No evidence could be obtained for the presence of diphenyl-lead dinitrate, which might conceivably have been formed by the reaction :

$$PbPh_3^+NO_3^- + Ag^+NO_3^- \longrightarrow PbPh_3^{++}(NO_3^-)_2 + Ag + C_6H_5\cdot \quad . \quad . \quad . \quad (3)$$

Such a reaction, between two positive ions (or at any rate between two positively-polarised groups), is *a priori* unlikely. In fact, no separation of silver occurred when dilute solutions of silver nitrate and triphenyl-lead nitrate were mixed.

Diphenyl. The results of the diphenyl estimations, carried out as described above, were as tabulated. In the first six experiments, the total volume of the mixed solutions was 400 ml. The yields are calculated on the basis of 100% for reaction (1) proceeding to completion, and all the phenyl radicals giving diphenyl by dimerisation, and is corrected on the assumption of an 85% recovery of diphenyl in the actual estimations, as in the control experiments. Gilman and Woods [6] reported yields of diphenyl in the region of 70% from reactions in which the quantities and conditions were those of expt. 7. The discrepancy between their work and ours has not been explained, but the important point is certainly that the results of expts. 7 and 8 are not strictly comparable with those of the first six experiments. Thus, from the dilute solutions of expts. 1—6, the silver separated first as a mirror, while with the larger concentrations of expts. 7 and 8 it appeared in finely divided form throughout the reaction mixture, indicating that the reaction may then have been largely heterogeneous in character.

Expt.	Molar concn. of reactants		Wt. of diphenyl formed (g.)	Average yield (%)
1, 2	0·005		0·004, 0·005	2·3
3, 4	0·01		0·023, 0·027	9·4
5, 6	0·015		0·054, 0·051	13·0
7, 8	6·45, 2·55 g.	$PbPh_4$ + $AgNO_3$ refluxed in 40 ml. of EtOH or in 40 ml. of EtOH + 25 ml. of C_6H_6 for 12 hr.	0·023, 0·016	29·5, 20·0

Reactions of the phenyl radicals. Diphenyl might be formed by dimerisation of phenyl radicals or by nuclear substitution in the benzene present :

$$2C_6H_5\cdot \longrightarrow C_6H_5\cdot C_6H_5 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

$$C_6H_5\cdot + C_6H_6 \longrightarrow C_6H_5\cdot C_6H_5 + H\cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Although reaction (5) seems *a priori* more likely in dilute solution, the small yields of diphenyl, increasing as the solutions become more concentrated, indicate that the dimerisation is in fact the more important reaction producing diphenyl. Most of the phenyl radicals must therefore react with the ethanol; the resulting $CH_3\cdot CH(OH)\cdot$ radicals may then dimerise to butane-2 : 3-diol or disproportionate to acetaldehyde and ethanol :

$$C_6H_5\cdot + CH_3\cdot CH_2\cdot OH \longrightarrow C_6H_6 + CH_3\cdot CH(OH)\cdot \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$2CH_3\cdot CH(OH)\cdot \longrightarrow CH_3\cdot CH(OH)\cdot CH(OH)\cdot CH_3 \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$2CH_3\cdot CH(OH)\cdot \longrightarrow CH_3\cdot CHO + CH_3\cdot CH_2\cdot OH \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Acetaldehyde. 400 ml. of the mixed solutions, 0·01M with respect to lead tetraphenyl and 0·005M with respect to silver nitrate, were refluxed. Excess of tetraphenyl-lead was used in order to minimise the possibility of reaction between acetaldehyde and unchanged silver nitrate. A stream of nitrogen was passed through the mixture, heated to 30°, thus blowing over any acetaldehyde into either an alcoholic solution of 2 : 4-dinitrophenylhydrazine or an aqueous solution of dimedone. The results were inconclusive; traces of the acetaldehyde derivatives of the test compounds were formed, but in quantities corresponding only to very small yields of acetaldehyde. It may be that some of the acetaldehyde was lost, because of its volatility, and that some reacted with silver nitrate. The latter possibility is discussed below.

Glycols. Estimations of glycol were carried out on the involatile residue from the preliminary distillations for diphenyl. This residue was extracted several times with cold water, in which any glycols should be soluble, and the other products insoluble. The aqueous extract was then treated with standard periodic acid solution (this reagent is specific for 1 : 2-glycols) and left for 15 min. (the recommended time for butane-2 : 3-diol). Excess of standard arsenite

[12] Grüttner and Grüttner, *Ber.*, 1918, **51**, 1293.

solution was then added, and back-titrated with iodine. Blank estimations were carried out, concurrently with the actual estimations, on solutions containing no glycol. In this way it was shown that a 1 : 2-glycol was present in quantities varying between 7% and 16% of the amount to be expected if all the phenyl radicals had reacted to give this product. These figures are, of course, lower limits, since some glycol must have been lost during the preliminary distillation and, in view of the small concentrations of the solutions, this may have been a significant fraction of the total quantity present.

Metallic silver. The yield is given in the following Table, as the percentage reduction at the conclusion of the reaction, of the silver nitrate originally present. As shown, there was effectively 100% reduction of the silver nitrate when the initial concentrations were equal or when the tetraphenyl-lead was in excess. This would be expected from equation (1) if it were not for the fact that, as mentioned above, only about 70% of the tetraphenyl-lead usually reacted with silver nitrate when the initial concentrations were equal. When the initial concentration of silver nitrate was twice that of tetraphenyl-lead, and the limiting value for the percentage reduction should therefore have been 50%, the actual figures (runs 6 and 7) were

Run	$AgNO_3$ (M)	$PbPh_4$ (M)	Reduction of $AgNO_3$ (%) at completion	k (l. mole^{-1} sec.$^{-1}$)
1	0·005	0·005	96	0·0083
2	0·01	0·01	98	0·0073
3	0·015	0·015	98	0·0083
4	0·005	0·01	100	0·0073
5	0·005	0·015	99·5	0·0069
6	0·005	0·0025	79·5	0·0087
7	0·01	0·005	86·5	0·0083
8	0·02	0·005	47·5	0·0074

79·5% and 86·5%. Similarly, for run 8, with a four-fold excess of silver nitrate over tetraphenyl-lead, the actual percentage reduction was 47·5% compared with the limiting value of 25% expected from reaction (1). It is therefore plain that a second reaction producing silver, besides (1), must take place. This might be the reaction of silver nitrate with acetaldehyde produced as mentioned above, or with the $CH_3{\cdot}CH(OH){\cdot}$ radicals themselves :

$$2AgNO_3 + CH_3{\cdot}CHO + C_2H_5{\cdot}OH \longrightarrow 2Ag + CH_3{\cdot}CO_2Et + 2HNO_3 \quad . \quad . \quad (9)$$

$$2AgNO_3 + 2CH_3{\cdot}CH(OH){\cdot} \longrightarrow 2Ag + CH_3{\cdot}CO_2Et + 2HNO_3 \quad . \quad . \quad (10)$$

On this basis, each phenyl radical could give rise to a further atom of silver, and this would account for the observed yields of metallic silver and also for the non-occurrence of acetaldehyde among the products. Silver nitrate was shown to react with acetaldehyde in ethanol at concentrations of the order used in the main experiments, but it was not possible to obtain self-consistent results for the kinetics of this reaction. A further possibility is that hydrogen atoms formed by reaction (5) might react at once with silver nitrate :

$$AgNO_3 + H{\cdot} \longrightarrow Ag + HNO_3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

In view of the small importance of reaction (5), however, most of the silver must have been formed through reactions (1), (9), and (10).

Summary.—It thus appears that tetraphenyl-lead and silver nitrate do not give phenyl-silver (except perhaps as a transient intermediate) in benzene–ethanol solutions of the concentrations used in the present work (~0·01M). Metallic silver and triphenyl-lead nitrate are formed and, presumably, phenyl radicals. Of the latter, not more than about 10% dimerise or react with the benzene, to give diphenyl. Most of the phenyl radicals remove hydrogen from the ethanol molecules present, and the $CH_3{\cdot}CH(OH){\cdot}$ radicals produced then either dimerise or disproportionate. Metallic silver is produced not only by reaction (1), but also by reaction of the acetaldehyde or $CH_3{\cdot}CH(OH){\cdot}$ radicals with the silver nitrate.

Kinetics of the reaction

For a given temperature and given concentrations of the reactants, about twenty determinations were made of the weight of silver produced after various times; the rate curve obtained by plotting the thiocyanate titre against time was reproducible. Interpretation of these results is confused by the simultaneous occurrence of at least two silver-producing reactions. Nevertheless, the main reaction (of silver nitrate with tetraphenyl-lead) is likely to be much more important than any other in the early stages. In agreement,

reasonable second-order plots were obtained from experimental results corresponding to the consumption of up to about one-third of the silver nitrate originally present; inclusion of later points produced a pronounced curvature and a markedly greater "scatter" in these plots, clearly because of the greater importance of secondary reactions in the later stages. Concentrations were varied as widely as possible, within the somewhat narrow limits set by solubility considerations and the method of silver estimation used. The figures in the foregoing Table all refer to a temperature of 60°. As shown, the second-order rate constants for different initial concentrations agree reasonably well with one another. With both reactants at initial concentrations of 0·005M, the following values of the second-order constant were obtained, at various temperatures:

T (°K)	323	328	333	338
k (l. mole^{-1} sec.$^{-1}$)	0·0035	0·0070	0·0083	0·0146

The usual plot gives a temperature coefficient of ~18,500 cal./mole for the reaction, and a temperature-independent factor of $\sim 10^{10}$ l. mole^{-1} sec.$^{-1}$.

Thus the initial process taking place between tetraphenyl-lead and silver nitrate in benzene–ethanol is the bimolecular reaction (1) or (2), giving metallic silver, triphenyl-lead nitrate, and phenyl radicals which either dimerise or react with the benzene and ethanol. Reactions (1) and (2) have been written in terms of ion-pairs, but might conceivably involve free ions: $Ag^+ + PbPh_4 \longrightarrow PbPh_3^+ + Ag + C_6H_5^\bullet$, etc., even though the dissociation of silver nitrate in 0·01M-solution is estimated as not more than about 1% from the very small conductivity of the solution. The corresponding reaction between silver nitrate and lead tetra-alkyls, indeed, was stated by Semerano and Riccoboni [7] to be virtually instantaneous in ionising solvents even at −80°, but extremely slow in non-ionising solvents. The present reaction in ethanol–benzene may represent an intermediate case. In any event, it is likely that the silver ions or silver-nitrate ion-pairs will be surrounded mainly by ethanol molecules, and the tetraphenyl-lead molecules mainly by benzene molecules. The fairly high temperature coefficient and low A factor of the reaction may thus be due to some extent to the differing characters of the solvation shells of the reactants.

The authors thank Professor C. E. H. Bawn for suggesting the subject of this investigation, and for help and encouragement during its course. One of them (W. T.) also thanks the D.S.I.R. for a Maintenance Grant.

Department of Inorganic and Physical Chemistry,
University of Liverpool. [*Received, January 19th,* 1956.]

---

646. *The Decomposition of Mercury Fulminate.*

By B. E. Bartlett, F. C. Tompkins, and D. A. Young.

The thermal decomposition of mercury fulminate has been investigated with particular attention to the effects of ageing, pre-irradiation, and crushing on the kinetics. Two forms, (i) freshly prepared, exponential, or white, and (ii) aged, brown, or cubic are distinguished. The method of conversion of one into the other, and the resultant changes of physical structure, have been studied. These results have proved useful in formulating mechanisms of decomposition in terms of the grosser imperfections (sub-grain boundaries) which separate the sub-grains of the crystal.

When mercury fulminate is heated to about 100°, it evolves mainly carbon dioxide and nitrogen, leaving a solid residue of uncertain composition. The conclusions of various workers concerning the kinetics and mechanism of decomposition differ in many respects. Farmer [1] distinguished two forms, the white and the brown, which behaved differently on decomposition, but did not analyse his results in any detail. The white and the brown

[1] Farmer, *J.*, 1922, 174.

variety undoubtedly correspond to our fresh and aged material respectively. Garner and Hailes [2] found that the acceleratory process of the decomposition was preceded by a period during which gas was slowly evolved at a constant rate. Grinding eliminated the initial process and enhanced the rate during the acceleratory period which was fitted, up to 20% decomposition, by the equation

$$\log\left\{\frac{dp}{dt} - \left(\frac{dp}{dt}\right)_0\right\} = k_1 t + \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $(dp/dt)_0$ represents the constant initial rate and k_1 is a velocity constant. The activation energy was 30·4—32·2 kcal./mole, compared with the value of 27·7 kcal./mole which Garner and Hailes had calculated from Farmer's results. Equation (1) was shown to be consistent with a chain mechanism in which the branching coefficient was a constant. It was suggested that reaction was initiated in the non-crystalline material which cements the grains of the crystal together. Only a few CNO ions in these cracks occupy sufficiently open positions for decomposition to occur; and occasionally the decomposition of one CNO ion uncovers two or more others so that a chain is set up. Grinding eliminates the linear process by increasing the number of reaction centres.

These conclusions were somewhat modified in a later paper,[3] the p–t plots being described by the expression

$$dp/dt = k_2 t^m \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where m for whole crystals varied from 11·2 to 22·8. The dependence (2) was described in terms of the non-uniform growth of reaction centres by transference of reaction from grain to grain at a few singular points on their mutual boundaries.

Vaughan and Phillips,[4] using Service material, considered the Prout–Tompkins equation [5]

$$\log p/(p_f - p) = kt + \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(p_f = final pressure corresponding to complete decomposition), which describes a branching chain mechanism with interference of branches, to be valid throughout the decomposition and obtained an activation energy of 26 kcal./mole for the acceleratory process. However, in a re-analysis of these results, Garner and Haycock [6] fitted the first 10% of decomposition after the linear process with the cubic equation (4)

$$p - p_0 = k_3(t - t_0)^3 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where p_0 and t_0 are approximately the co-ordinates corresponding to the end of the linear process. From this dependence they concluded that spherical nuclei are formed at the point (p_0, t_0) and thereafter grow at a constant rate.

The present investigation was undertaken to extend these results and to correlate the different viewpoints into a coherent theory consistent with our present and more detailed knowledge of the structure of ionic crystals.

Experimental

Materials.—" Fresh " fulminate was prepared by precipitation from a solution of the salt in equal volumes of water, ethyl alcohol, and ammonia solution (d 0·880) by dropwise addition of acetic acid with stirring at room temperature. This procedure gave crystals which, after filtration and drying, passed through a 400-mesh B.S.S. sieve. " Aged " fulminate results from the storage of fresh material for about 2 years.

The apparatus used and experimental procedures followed were similar to those outlined by Thomas and Tompkins.[7]

[2] Garner and Hailes, *Proc. Roy. Soc.*, 1933, *A*, **139**, 576.
[3] *Idem*, *J.*, 1933, 1393.
[4] Vaughan and Phillips, *J.*, 1949, 2741.
[5] Prout and Tompkins, *Trans. Faraday Soc.*, 1944, **40**, 488.
[6] Garner and Haycock, *Proc. Roy. Soc.*, 1952, *A*, **211**, 335.
[7] Thomas and Tompkins, *ibid.*, 1951, *A*, **210**, 111.

Results

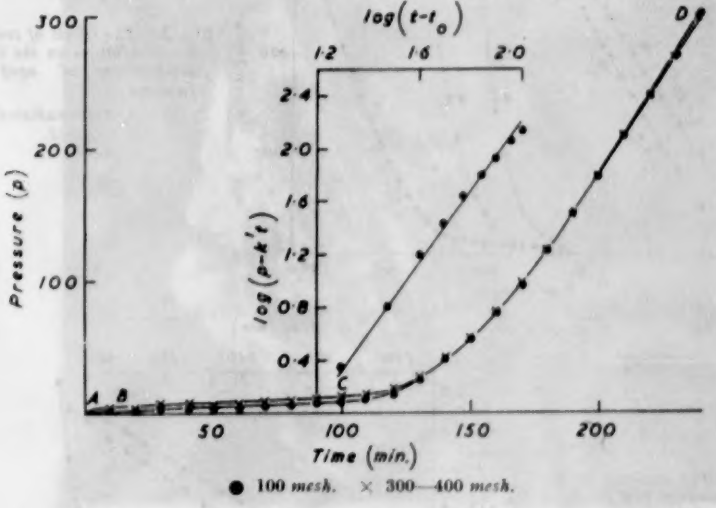
Aged Material.—Typical p–t plots for the decomposition of the two samples of crystal size (i) 300—400 mesh, (ii) 100 mesh are given in Fig. 1, which show that there is little effect of particle size on the rate. For ease of discussion, the plot has been divided into four sections: (i) the initial decay AB, (ii) the linear process BC, (iii) the acceleratory process CD, and (iv) the final decay process after D. The fourth section is not illustrated in Fig. 1 because we are only interested in (i), (ii), and (iii).

The initial decay follows a first-order law

$$\log\left\{p_D/(p_D - p)\right\} = k_D t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where p_D is the pressure at the completion of the process and corresponds to *ca.* 0·4% decomposition. Preliminary measurements indicate that the activation energy is around 5 kcal./mole.

Fig. 1. *The thermal decomposition of aged mercury fulminate for samples of different crystal size.*



● 100 *mesh.* × 300—400 *mesh.*

The acceleratory period can be fitted with Garner's expression (4) up to 10% decomposition but a better fit, extending both to higher and to slightly lower percentage decomposition, is given by

$$p - p_D = k_3(t - t_0)^3 + k^1 t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where k^1 is the rate constant of process (ii), and t_0 refers to the co-ordinate at the end of the linear process. The activation energy obtained from the temperature coefficient of k_3^1 is 27 kcal./mole.

Effect of Pre-irradiation.—Illumination with mercury resonance radiation (λ 2537 Å) causes evolution of gas at a constant rate for 120 minutes, after which the rate slowly decreases. The rate of gas evolution, which corresponds on average to about 2·5% decomposition per hour, is proportional to the square of the intensity of illumination at constant temperature, suggesting that the two molecules of fulminate (or two fulminate anions) are engaged in the act of decomposition. A considerable amount of gas is given off after cessation of irradiation and this "dark" rate, as with potassium azide and barium styphnate monohydrate, follows a first-order decay law consistent with desorption of gaseous product that had accumulated on internal and external surfaces during photolysis.

The effect of pre-irradiation at constant intensity for varying times on the subsequent thermal decomposition at 108° was also studied. It was found that (i) the initial decay process is eliminated, (ii) the value of p_0 is substantially unaffected, though t_0 is decreased, (iii) the applicability of the cube law is extended to 20% decomposition though the point of inflection of

the p–t plot is lowered from 65 to 50% decomposition, and (iv) the velocity parameters are related by

$$k_3 \text{ (irradiated)} - k_3 \text{ (unirradiated)} \propto k^1 \text{ (irradiated)} - k^1 \text{ (unirradiated)}$$

With increasing periods of pre-irradiation, k_3 and k^1 approach saturation values about three times greater than those found for unirradiated aged material, and t_0 decreases linearly.

Effect of Crushing.—Crushing (*i.e.*, rolling the rounded end of a glass rod over crystals spread thinly on a glass plate) has similar effects on the subsequent thermal decomposition to pre-irradiation. The initial decay process is removed, t_0 is decreased, and the linear and the cubic rate are increased proportionally (Fig. 2). Pre-irradiation of such crushed crystals, however, does not further increase the rates although t_0 continues to decrease. The values of k_3 obtained

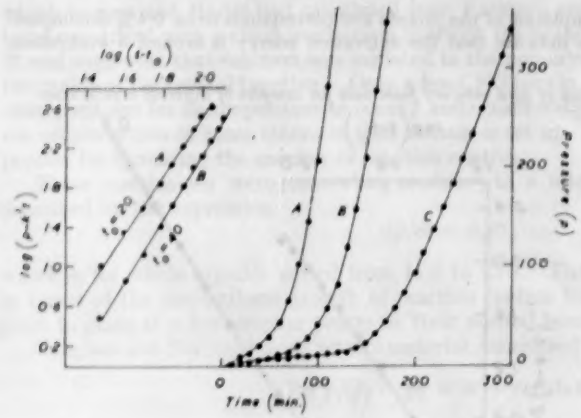


FIG. 2. *The effects of crushing and pre-irradiation on the thermal decomposition of aged mercury fulminate.*

A, Pre-irradiated.
B, Crushed.
C, Aged.

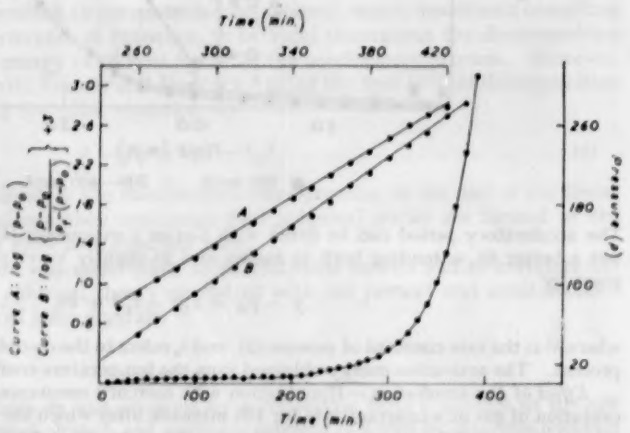


FIG. 3. *The analysis of the decomposition plot for fresh mercury fulminate.*

A, $\log p$ against t.
B, Prout–Tompkins equation.

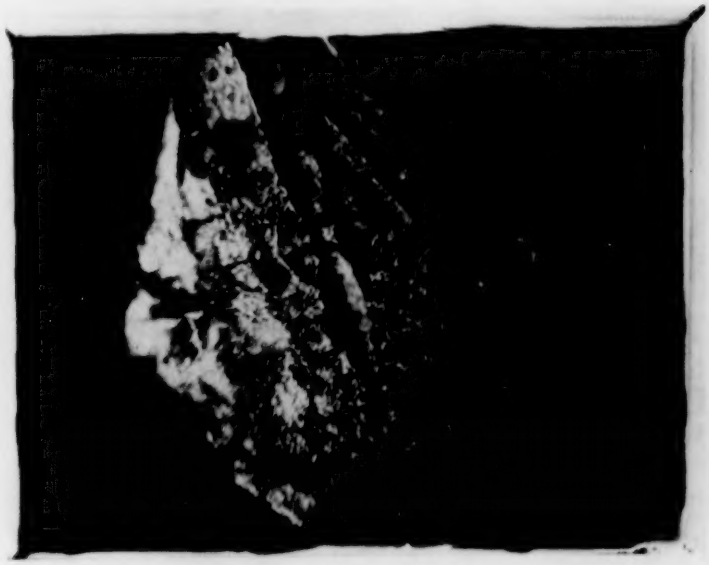
with crushed crystals are within 10% of those obtained from uncrushed, aged crystals which had been pre-irradiated for a time sufficient to attain the maximum value of k_3 (*ca.* 1 hr.).

Freshly Prepared Material.—A typical decomposition curve is shown in Fig. 3. The principal differences from the decomposition of aged material are (i) the linear process extends over twice the time found for aged fulminate, although p_0 is less ($\frac{1}{3}$—$\frac{1}{4}$), and (ii) the acceleratory process below *ca.* 35% decomposition can be fitted by the exponential relation

$$\log (p - p_0) = k_0 t + \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The suitability of equation (7) below 2% decomposition is greater for samples precipitated by dilute acetic acid from ammoniacal solution than for those obtained simply by dilution with

Cracks, roughly parallel and about 10 μ *apart, produced in fresh mercury fulminate crystals by exposure to ultraviolet light.*



[*To face p.* 3326.

water. The maximum rate of decomposition occurs at about 50% decomposition. Freshly prepared material obeys the cube law up to 50% decomposition after crushing and up to 20% decomposition after pre-irradiation (Fig. 4).

Since both ammonia and water are used in the preparation of mercury fulminate, layers of these reagents adsorbed at the surface of freshly prepared material might contribute to the ageing process. Consequently, fresh material was stored for 48 hours in presence of (i) 10 mm. pressure of water vapour, and (ii) moist ammonia vapour, but it was found that the subsequent thermal decomposition was unaffected in both cases. With aged crystals, treatment with water vapour had no effect except slightly to reduce the value of p_D, though after exposure to moist ammonia vapour the subsequent thermal decomposition was found to proceed according to an exponential law [equation (7); see Fig. 5].

Microscopical Observations.—When aged crystals (60—100 mesh) were irradiated with ultra-violet light of wavelength 2537 Å, cracks were produced at the surface (see Plate), the first of these appearing after five minutes' irradiation. The number increased to a maximum in the same manner as k^1 and k_3 over the same period. No additional cracks were seen to form during the subsequent thermal decomposition and no discrete nuclei were apparent at any stage, the

FIG. 4. *The decomposition of fresh crystals of mercury fulminate after (A) crushing and (B) pre-irradiation.*

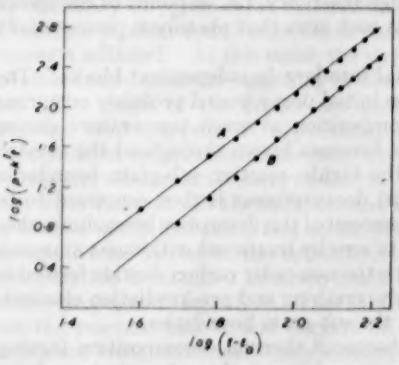
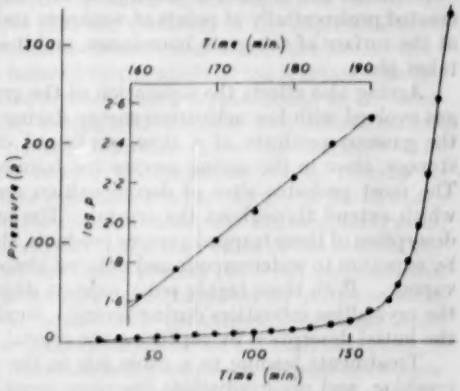


FIG. 5. *The decomposition of aged mercury fulminate after exposure to moist ammonia vapour.*



whole crystal gradually becoming brown as the reaction proceeded. The cracks created by pre-irradiation could be removed by treatment with moist ammonia vapour but not with water vapour alone, and the exponential law was then obeyed.

Summarising the conversion processes diagrammatically we have:

Exponential (fresh, white)

Treatment with moist ammonia vapour (except after crushing) ↑ | ↓ Ageing, with or without subsequent irradiation, or crushing; or pre-irradiation

Cubic (aged, brown)

DISCUSSION

The Reactant Matrices.—It is becoming increasingly evident from published work on silver oxalate,[8] from current work on azides, and from the present results on mercury fulminate, that changes occurring in the solid after preparation (termed ageing) are largely responsible for lack of agreement amongst the results of various workers. As with silver oxalate, the kinetic expressions applicable to the acceleratory process of the decomposition of fresh and aged mercury fulminate are different, although the activation energies are the same. These differences are therefore associated with changes of structure of the material and not with alternative reaction mechanisms.

All solids contain imperfections, and apart from the external surface itself, the most

[8] Tompkins, *Trans. Faraday Soc.*, 1948, **44**, 206; Finch, Jacobs, and Tompkins, *J.*, 1954, 2053.

extensive are low-angle or sub-grain boundaries which divide the crystals into blocks or sub-grains of linear dimensions 1—10 μ. These boundaries often comprise arrays of parallel edge dislocations in the principal lattice planes of the crystal (tilt boundaries), as, for example, in polygonised sodium chloride crystals,[9] but more generally consist of two-dimensional arrays of dislocations with mixed character, *e.g.*, screw and edge dislocations. These disordered regions generally arise from the presence of impurities and are known to have enhanced reactivity. We believe that they play an important role in the decomposition of ionic crystals generally. In contrast, we have little evidence which suggests that vacancies or other isolated defects are effective in contributing to the kinetics of decomposition of this material.

Effects of Crushing, Grinding, and Pre-irradiation.—During crushing, the crystals fracture along the original sub-grain boundaries,[10] individual blocks being formed in a cold-worked condition. These blocks are probably covered with a superficial layer of decomposed fulminate due to the frictional heat generated during crushing. Pre-irradiation has a similar effect in causing separation into blocks since cracks which are visible at a magnification of 500 are produced by the light at intervals of 10—15 μ. Even though actual fragmentation, such as occurs in crushing, does not take place, the result is nevertheless the division of the crystal into largely independent blocks. These cracks are created preferentially at points of weakness and high reactivity, *i.e.*, at points of emergence at the surface of sub-grain boundaries, and it is at such sites that photolysis preferentially takes place.

Ageing also effects the separation of the crystal into largely independent blocks. The gas evolved with low activation energy during the initial decay period probably comprises the gaseous products of a slow, prolonged decomposition at room temperature during storage, since in the ageing process the fulminate becomes brown throughout the crystal. The most probable sites of decomposition are the highly reactive sub-grain boundaries which extend throughout the crystal. The initial decay process is thus conceived to be desorption of these trapped gaseous products, the amount of this desorption being diminished by exposure to water vapour and reduced almost to zero by treatment with moist ammonia vapour. Both these highly polar vapours displace the non-polar carbon dioxide formed in the crystalline interstices during ageing. Similarly, crushing and pre-irradiation eliminate the initial desorption by rupturing the crystal at the sub-grain boundaries.

Treatments leading to a cubic law in the subsequent thermal decomposition (ageing, crushing, and pre-irradiation) therefore cause decomposition at the sub-grain boundaries such that the sub-grains of the reactant phase become predominately non-contiguous, *i.e.*, they become separated from each other by barriers of reaction product. The cubic relation describes the kinetics of processes which occur within the individual blocks themselves.

Moist ammonia vapour, which reconverts cubic material produced by ageing or pre-irradiation into the exponential (fresh) form, does so by healing the barriers or cracks produced by the previous treatment. Capillary condensation of water vapour followed by dissolution of ammonia provides a good solvent for mercury fulminate, so that the surface mobility of the constituent ions is enhanced. During removal of the solvent, unchanged fulminate is deposited in the sub-grain boundaries or cracks which then consist of reaction product, formed during ageing or photolysis, and freshly deposited fulminate. The essential condition for obedience to the cubic equation, the non-contiguity of the sub-grains, is no longer maintained and the exponential law is then valid (see below). These results suggest that the exponential relationship is associated with the propagation of the decomposition from block to block.

The Linear Process.—The constant rate, with an activation energy of 19 kcal./mole, is readily conceived as an interfacial reaction proceeding into each block from surfaces which have been sufficiently well nucleated (the first stages of the contracting-envelope concept). Both crushing and pre-irradiation, which cause a three- to four-fold increase in the rate of

[9] (*a*) Cottrell, "Dislocations and Plastic Flow in Crystals," Oxford, 1953; (*b*) Dekeyser, Bristol Conference of the Physical Society, July, 1954; (*c*) Amelinckx, Van der Vorst, Gevers, and Dekeyser, *Phil. Mag.*, 1955, **46**, 450.

[10] Relation of Properties to Microstructure, Amer. Soc. Metals, 1954, p. 163.

this process but do not affect the activation energy, produce cracks, thereby increasing the area of the nucleated surface and therefore the rate of decomposition. Although the period over which the process extends and the extent of decomposition, as measured by p_0, differ for the aged and the fresh material, the identical kinetics and activation energies are evidence that the same mechanism is operative for both.

The Acceleratory Process.—With material which obeys a cube law, (i) the acceleratory process starts at the same p_0 value (same extent of decomposition) for all temperatures even though the preceding linear process may have been accelerated by preliminary crushing or pre-irradiation; (ii) the ratio of k_3 (the cube rate constant) to k^1 (the linear rate constant) remains constant at constant temperature when both k_3 and k^1 are increased to their maximum values by pre-irradiation; (iii) the linear process continues independently after point C (p_0, t_0); and (iv) at some point along CD, the rates of decomposition of the linear and the acceleratory process are equal, but since the activation energies are different (19, 27 kcal./mole), the respective pre-exponential factors have different orders of magnitude ($10^{4\cdot5}$: 1; acceleratory : linear).

Conclusions (iii) and (iv) are also valid for the decomposition of material which obeys the exponential law.

Since the linear process is probably an interface reaction at the surface of the blocks, the constancy of p_0 for cubic material requires that the thickness of the superficial layer of reaction product round each block shall attain a critical value before the acceleratory process is initiated. At this point, the strain induced by the misfit at the reactant–product interface causes secondary cracking in directions predominantly perpendicular to the interface. The cusps of the cracks are probably propagated stepwise and discontinuities (cleavage steps) appear at approximately regular intervals down the cracks.[10] The decomposition spreads simultaneously over the faces of the secondary cracks, thereby increasing the volume strain energy until this is relieved, at least in part, by slip at the cleavage steps when isolated sub-blocks, identified with the classical mosaics of the original crystal, are formed within the sub-grains of the parent crystal. The high value of the ratio of the pre-exponential factors of the acceleratory and the linear process ($10^{4\cdot5}$: 1) suggests that when reaction is initiated in a sub-block it is completely decomposed by a co-operative process propagated rapidly.[11] The sub-block, now wholly decomposed, detaches itself from the reactant matrix and triggers off the decomposition of an adjacent sub-block,[12] the process being statistically independent of direction and requiring a thermal activation energy of 27 kcal./mole. The product matrix thus comprises a conglomerate of sub-blocks, approximately hemispherical in shape and bounded by the original sub-grain boundaries. The whole process therefore corresponds to three-dimensional growth of reaction centres, all of which are created at approximately the same time t_0, the appropriate rate expression being $p = k_3(t - t_0)^3$, where the parameter k_3 contains a term denoting the total number of blocks in the crystal.

With fresh material, the value of p_0 is smaller ($\frac{1}{4}$—$\frac{1}{3}$) than that obtained with aged material, indicating that the total amount of decomposed inter-subgranular material is less at t_0. It is suggested therefore that the critical thickness of the superficial layer of product is attained only over patches of the surfaces of the sub-grains. At these areas, as with cubic material, secondary cracks are locally produced, but instead of ultimately terminating, as in cubic material, at fully decomposed sub-grain boundaries, some will meet undecomposed boundary material. The sub-grains of fresh material are not largely independent non-contiguous domains, but are linked to each other by bridges of the undecomposed reactant. The sub-block formation does not spread uniformly throughout the individual sub-grains as in cubic material, but extends tree-like through the whole crystal *via* the bridges in a branching manner, because cracking can only originate in each sub-grain from that part of the surface which is covered with a product layer of the critical thickness. The mechanism of the sub-block decomposition and the " triggering off " of adjacent sub-blocks is the same as in cubic material, and hence the activation energy is unchanged.

[11] (*a*) Acock, Garner, Milsted, and Willavoys, *Proc. Roy. Soc.*, 1947, *A*, **189**, 308; (*b*) Hartshorne and Roberts, *J.*, 1951, 1097.

[12] Burgers, *Proc. k. ned. Akad. Wetenschap.*, 1947, **50**, 595.

The initial reaction centres present at t_0 are largely concentrated at the external surfaces, since only here is the product layer of critical thickness complete; however, many of the initial centres of reaction do not continue to propagate the decomposition in every direction since this is only possible where adjacent sub-blocks are already present. Further, in transference of reaction from block to block more than one bridge is normally available so that branching takes place. An exponential rate law can thus be expected.[2] It must be emphasised that although the acceleratory process is associated with the higher activation energy (27 kcal./mole) this energy requirement is sufficient to initiate the decomposition of a chain of $10^{4\cdot5}$ molecules of fulminate, whereas, in the linear process the low energy of 19 kcal./mole has to be gained for each molecule (or pair of molecules) decomposing. Consequently, the linear process, still apparent at low percentage decomposition, is quickly swamped by the acceleratory process, the speed of travel of which is so much greater through the crystal. Further, the ageing process which extends over months is so slow that relaxation processes have ample time to occur whereas in the rapid process of " bridging " the sub-grains during decomposition, these processes cannot take place; indeed, this is one of the main factors in block-to-block infection.

Finally one would expect that in the initial stages the rate of the exponential process would be slower than that of the cubic process since the number of reaction centres is smaller. The experimental results are in accord with this. Similarly, depending on the number of initial centres of reaction which continue to grow, interference to the branching would be expected. Consequently, for fresh material, the Prout–Tompkins equation should be valid over a greater range than the simple exponential expression, as is illustrated in Fig. 3. It is considered that the service material used by Vaughan and Phillips probably corresponds to our aged material.

The activation energy of 27 kcal./mole obtained here is in good agreement with that recorded by Vaughan and Phillips (26 kcal./mole) and that calculated from Farmer's results (27·7 kcal./mole), but is appreciably less than the value given by Garner and Hailes for single crystals. Their higher values may be due to self-heating, which cannot be entirely eliminated by use of a hydrogen atmosphere since reaction proceeds throughout the crystal and is not confined to those surfaces of the crystal in contact with cooling gases.

In conclusion, it is clear from the present work, from that previously reported on the silver oxalate decomposition, and from unpublished results with azides, that ageing brings about changes in the physical structure of freshly prepared material which determine to varying degrees the kinetics of the decomposition. The marked similarity in the behaviour of mercury fulminate and silver oxalate also suggests that the present theoretical approach in terms of the grosser imperfections—a theory which may be regarded as an extension and generalisation of that previously suggested on the basis of results obtained on silver oxalate—may have a much wider applicability to other solid decompositions.

We thank Mr. G. W. C. Taylor for supplying materials and for helpful discussions.

Chemistry Department,
Imperial College of Science and Technology,
South Kensington, London, S.W.7.

[*Received, March 12th,* 1956.]

647. *The Decomposition of Lead Styphnate Monohydrate.*

By F. C. Tompkins and D. A. Young.

The thermal decomposition of lead styphnate monohydrate proceeds smoothly between 195° and 229° with an activation energy of 33 kcal./mole. The mechanism of decomposition is similar to that previously proposed for barium styphnate monohydrate.

Hailes [1] found that large crystals of lead styphnate monohydrate decomposed smoothly between 200° and 228° with an activation energy of 46·7 kcal./mole according to an exponential expression consistent with the branching of linear reaction chains, but Garner, Gomm, and Hailes [2] analysed the decomposition plot according to a power law $p = ct^m$, where m varied between 0·88 and 4·43. More recently, Zingaro [3] measured the rate of dehydration of finely ground crystals of the monohydrate between 115° and 145°, and the present authors [4] investigated the dehydration and decomposition of the related compound, barium styphnate monohydrate. Conclusions differing from those of Hailes *et al.* were reached and the present paper extends our discussion [4] to the corresponding lead salt.

Experimental.—Regular, finely divided crystals of lead styphnate monohydrate, prepared from aqueous solution, were kindly supplied to us by Mr. G. W. C. Taylor. The crystals were not ground but passed through a 100-mesh B.S.S. sieve. The decomposition was carried out in an apparatus developed from a design by Thomas and Tompkins.[5]

Results and Discussion.—Small crystals of lead styphnate monohydrate decompose smoothly between 195° and 229°. Self-heating of the reactant becomes evident at 229° and above 235° the decomposition develops unfailingly into explosion. It was thus not possible, with this sample, to investigate the decomposition of a possible "hydrated" form as was done with large crystals of the barium salt at higher temperatures.[4] Typical plots of pressure against time are illustrated in Fig. 1; interruption of a run, as with the barium salt at low temperatures, introduced no new features. The point of inflection occurs at approximately 30% decomposition instead of at 50% for the barium salt, but the plots of the acceleratory period are approximately parabolic, as found with barium styphnate, and a suitable rate constant can be derived when the results are plotted as $p^{\frac{1}{2}}$ against t (Fig. 2). The complete kinetic expression is:

$$p = k(t - t_0)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $t_0 \approx 10$ minutes and the activation energy calculated from the temperature coefficient of log $k^{\frac{1}{2}}$ is 33 kcal./mole, the corresponding figure for the barium salt being 36·5 kcal./mole. The reproducibility is better than $\pm 2\%$.

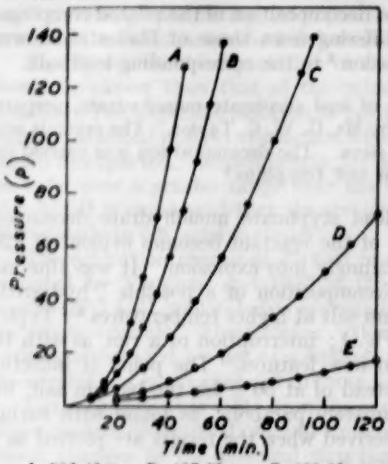
Calculation from Zingaro's results shows that the dehydration of ground crystals proceeds with an activation energy of *ca.* 18 kcal./mole and would be largely complete at 200° within 7 minutes, *i.e.*, in a time shorter than that (20 minutes) required for the inception of the parabolic dependence at the same temperature. Since it was shown that the rates of dehydration of ground and of small crystals of barium styphnate monohydrate are approximately the same we conclude that the decomposition occurs also in the anhydrous regions of small crystals of the lead salt. Deviations from eqn. (1) are ascribed to the simultaneous occurrence of dehydration during the early stages of decomposition.

The only feature in which the decomposition plots for small crystals of the barium and the lead salt differ is that the sigmoid decomposition plot for lead styphnate is not symmetrical, the decay period having the characteristic form associated with decompositions of the "contracting-envelope" type.[6] The form of the plots obtained for small crystals,

[1] Hailes, *Trans. Faraday Soc.*, 1933, **29**, 544.
[2] Garner, Gomm, and Hailes, *J.*, 1933, 1393.
[3] Zingaro, *J. Amer. Chem. Soc.*, 1954, **76**, 816.
[4] Tompkins and Young, *Trans. Faraday Soc.*, 1956, **51**, in the press.
[5] Thomas and Tompkins, *Proc. Roy. Soc.*, 1951, *A*, **209**, 111.
[6] "Chemistry of the Solid State," ed. W. E. Garner, Butterworths, London, 1955.

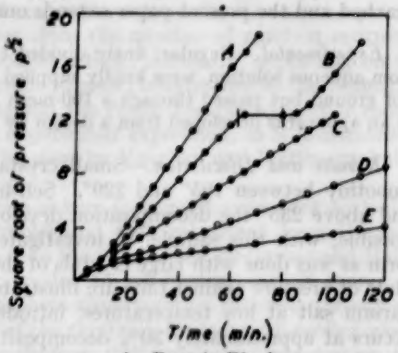
however, differs from those obtained by Garner *et al.* and by Hailes for large crystals, and the activation energies are different. It seems possible that with large single crystals the activation energy of 46·7 kcal./mole refers in part to the decomposition of the " hydrated " form since the corresponding value obtained by us for the " hydrated " barium salt was also high (52·6 kcal./mole). By analogy with the results for barium styphnate, which decomposes at similar rates with approximately the same activation energy and heat of decomposition, self-heating cannot provide the reason for higher value obtained by Hailes [1] below 229°. Since our activation energies for the barium and the lead salt differ by only 10% it is probable that the same primary process, the activation of an exposed or " surface " styphnate ion, is operative in each case.

FIG. 1. *The decomposition of lead styphnate monohydrate: pressure–time plots. The acceleratory period is approximately parabolic.*



A, 502·4° K. *B*, 497·5° K. *C*, 490·0° K.
D, 487·6° K. *E*, 468·0° K.

FIG. 2. *The decomposition of lead styphnate monohydrate: (pressure)½ plotted against time.*



A—E, as in Fig. 1.

Calculations using the geometrical methods described by Mampel [7] and by Jacobs and Tompkins [8] show that, since the maximum velocity occurs at 30% decomposition, the kinetics cannot be ascribed to either (i) initial increasing surface coverage by reaction product of all sub-grains nucleated simultaneously, followed by contraction of the interfaces thus created, since a parabolic acceleratory period would give a maximum rate below 10% decomposition, or (ii) nucleation, taking place according to a first-order law, of particles which decompose with a " contracting-envelope " interface, since this leads to a square-law dependence only to about 6% decomposition.

There seems, in fact, no reason to change the mechanism proposed for the decomposition of barium styphnate, *viz.*, nucleation of sub-grains at the edges and progression of the reaction into the grains with a non-coherent interface, the only difference being that the restriction of a predominantly faster rate of penetration of the reaction along one axis for the barium salt can be relaxed in the decomposition of lead styphnate.

CHEMISTRY DEPARTMENT,
IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY,
SOUTH KENSINGTON, LONDON, S.W.7.

[*Received, March 12th*, 1956.]

[7] Mampel, *Z. phys. Chem.*, 1940, **187**, *A*, 43, 235.
[8] Ref. 6, Chap. 7.

648. *Alkenylation with Lithium Alkenyls. Part XIII.** 1-*Methylvinyl-lithium* (iso*Propenyl-lithium*).

By (the late) E. A. Braude and E. A. Evans.

*iso*Propenyl bromide is readily converted into the lithium alkenyl, $CH_2{:}CMe{\cdot}Li$ by direct metallation. All five possible methyl-substituted vinyl-lithium derivatives $CR_2{:}CR{\cdot}Li$ (R = H or Me) are now known.

*iso*Propenyl-lithium reacts with carbon dioxide, to give α-methylacrylic acid, with aldehydes to give secondary alcohols (23—72%), and with ketones to give the expected tertiary alcohols (65—88%).

The acid-catalysed rearrangements of the alcohols $HO{\cdot}CRPh{\cdot}CMe{:}CH_2$ (R = H, Me or Ph) are described, and the spectral properties of the resulting substituted cinnamyl alcohols are discussed.

This paper describes the formation and some reactions of 1-methylvinyl-lithium (*iso*propenyl-lithium), $CH_2{:}CMe{\cdot}Li$. 2-Methylvinyl-lithium (propenyl-lithium),[1] as well as the three more highly methyl-substituted derivatives of the type $CR_2{:}CR{\cdot}Li$, have been described previously,[2,3] so that this series of lithium alkenyls, which are proving useful synthetical reagents,[4] is now completed. *iso*Propenyl-lithium is employed here for the preparation of a number of allylic alcohols required in connection with studies on anionotropic rearrangements.[5]

*iso*Propenyl bromide underwent direct metallation with ease under the usual conditions. Very little, if any, Wurtz-type coupling or other side reactions occurred, and no 2 : 3-dimethylbutadiene was isolated; yields as high as 88% were attained in subsequent reactions, *e.g.*, with acetophenone (see below). Carboxylation of *iso*propenyl-lithium afforded α-methylacrylic acid in low yield (about 20%), comparable to that obtained in other cases; as with 1 : 2-di- and 1 : 2 : 2-tri-methylvinyl-lithium, and in contrast to 2-methyl- and 2 : 2-dimethyl-vinyl-lithium, only traces of ketonic products were obtained. It is not clear at present whether this is due to a steric effect of the 1-methyl group or to some other cause. After the present investigation had been completed, the earlier work of Petrov [6a] and Nesmeyanov [6b] came to our notice. These authors carried out the carboxylation of *iso*propenyl-lithium, isolating, besides α-methylacrylic acid, a small amount of di*iso*propenyl ketone. They also effected metathetical reactions of *iso*propenyl-lithium with chlorotrimethylsilane and with several metal halides.

Reaction of *iso*propenyl-lithium with aldehydes and ketones gave the secondary or tertiary alcohols (see Table), the latter generally in higher yields.

Reactions of iso*propenyl-lithium with aldehydes and ketones.*

Carbonyl compound	Product	Yield (%)
Benzaldehyde	$HO{\cdot}CHPh{\cdot}CMe{:}CH_2$ (I)	72
Acetophenone	$HO{\cdot}CMePh{\cdot}CMe{:}CH_2$ (II)	88
Benzophenone	$HO{\cdot}CPh_2{\cdot}CMe{:}CH_2$ (III)	65
Acraldehyde	$CH_2{:}CH{\cdot}CH(OH){\cdot}CMe{:}CH_2$ (IV)	23
Crotonaldehyde	$CHMe{:}CH{\cdot}CH(OH){\cdot}CMe{:}CH_2$ (V)	38
Mesityl oxide	$CMe_2{:}CH{\cdot}CMe(OH){\cdot}CMe{:}CH_2$ (VI)	74

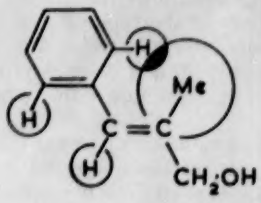
Treatment of the alcohols (I, II, and III) obtained from benzaldehyde, acetophenone, and benzophenone respectively with dilute mineral acid resulted in rearrangement to the corresponding substituted cinnamyl alcohols (VII, VIII, and IX); in the second case

* Part XII, *J.*, 1955, 3337.

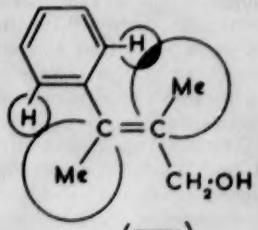
[1] Braude and Coles, *J.*, 1951, 2078; cf. Braude and Evans, *J.*, 1955, 3334.
[2] Braude and Evans, *J.*, 1955, 3324, 3331.
[3] Dreiding and Pratt, *J. Amer. Chem. Soc.*, 1954, **76**, 1902.
[4] Braude, in "Progress in Organic Chemistry," ed. J. W. Cook, 1955, Vol. III, chapter 4, p. 172.
[5] Cf. Braude, Coles, Evans, and Timmons, *Nature*, 1956, **177**, 1167.
[6] (*a*) Petrov and Nikishin, *Doklady Akad. Nauk U.S.S.R.*, 1953, **93**, 1049; *Chem. Abs.*, 1955, **49**, 841; (*b*) Nesmeyanov, Borisov, and Novikova, *Doklady Akad. Nauk U.S.S.R.*, 1954, **98**, 289; *Chem. Abs.*, 1955, **49**, 5276.

simultaneous dehydration occurred, to yield 2-methyl-3-phenylbutadiene (X). α-Methylcinnamyl alcohol (VII) was characterised by oxidation to α-methylcinnamaldehyde; its geometrical configuration was not proved, but is almost certainly the less hindered form shown, in which the phenyl and hydroxymethyl groups are *trans*-oriented. Even so, the ultraviolet-light absorption ($\lambda_{max.}$ 2440 Å, ε 13,000) differs significantly from that of cinnamyl alcohol ($\lambda_{max.}$ 2510 Å, ε 19,000) undoubtedly owing to steric interference between the phenyl and the methyl groups which prevents the styryl chromophore from becoming uniplanar. This effect is more marked in the dimethyl derivative (VIII) ($\lambda_{max.}$ 2350 Å, ε 5000). Both these alcohols exhibit, not only a reduced absorption intensity, but also considerable hypsochromic shifts of the maxima, signifying appreciable hindrance to planarity.[7]

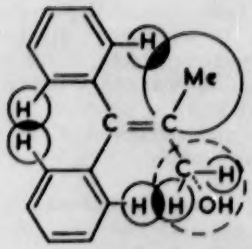
α-Methyl-β-phenylcinnamyl (2-methyl-3 : 3-diphenylallyl) alcohol (IX) has been obtained by Ziegler and Tiemann[8] from 1-methyl-2 : 2-diphenylvinylmagnesium bromide and formaldehyde. It shows an absorption maximum (λ 2420 Å, ε 14,000) practically identical with that of the monophenyl compound (VII); as with other compounds containing the 1 : 1-diphenylethylene unit,[9] the cross-conjugated phenyl group is entirely ineffective.



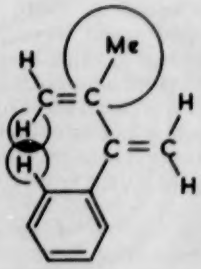
(VII)



(VIII)



(IX)



(X)

Similarly, the absorption of 2-methyl-3-phenylbuta-1 : 3-diene (X) ($\lambda_{max.}$ 2230 Å, ε 10,000) corresponds to that of the partial diene chromophore and is quite different from that of 1-phenylbuta-1 : 3-diene. The apparently almost complete lack of interaction in these cases must again be ascribed to steric hindrance * rather than (as has sometimes been suggested) to the cross-conjugated arrangement as such; less-hindered cross-conjugated systems, though they absorb at shorter wavelengths than their straight-conjugated analogues, show appreciable bathochromic displacement due to the crossed chromophore (*e.g.*, hexatriene,[10] $\lambda_{max.}$

* A non-planar *s-cis*-conformation for the diene (X) instead of the *s-trans*-conformation shown is equally compatible with the spectral data.

[7] Cf. Braude, *Experientia*, 1955, **11**, 457; Braude and Sondheimer, *J.*, 1955, 3773.
[8] Ziegler and Tiemann, *Ber.*, 1922, **55**, 3406.
[9] Jones, *J. Amer. Chem. Soc.*, 1943, **65**, 1820; Braude, Bruun, Weedon, and Woods, *J.*, 1952, 1419.
[10] Woods and Schwartzmann, *J. Amer. Chem. Soc.*, 1948, **70**, 3394.

2550 Å; 3-methylenepenta-1 : 4-diene,[11] $\lambda_{max.}$ 2310 Å; * butadiene,[12] $\lambda_{max.}$ 2170 Å; benzophenone, $\lambda_{max.}$ 2510 Å; benzaldehyde, $\lambda_{max.}$ 2420 Å). It is noteworthy that the overall effect of the β-methyl substituent in the alcohol (VIII) is larger than that of the β-phenyl substituent in the analogue (IX), although hindrance should be less severe in the former. This shows that the second phenyl group evidently does interact to some extent, thus compensating, in part, for the larger steric effect. It is probable that, in fact, both phenyl rings are tilted by about the same angle with respect to the plane of the double bond; similar observations have been made for di- and tri-phenylmethyl derivatives [13] and for diphenyl sulphones.[14]

Reaction of *iso*propenyl-lithium with dimethylformamide gave, instead of the expected α-methylacraldehyde, a low yield of a conjugated diene-aldehyde $C_7H_{10}O$, isolated as the 2 : 4-dinitrophenylhydrazone. A similar product was previously obtained [3] from propenyl-lithium.

Experimental

For general methods, see Part IX.[1]

1-*Methylvinyl-lithium* (*isopropenyl-lithium*).—Bromine (800 g.) was added dropwise to a stirred solution of α-methylacrylic acid (400 g.) in carbon disulphide (800 ml.) at 0°. After 15 hr., the solvent was distilled off, giving αβ-dibromo-α-methylpropionic acid, m. p. 46—48°. The dibromo-acid (500 g.) was refluxed for 6 hr. with anhydrous pyridine (1 l.). After cooling, a slight excess of ice-cold concentrated hydrochloric acid was added. Steam-distillation gave crude 2-bromopropene, which was washed with 2N-hydrochloric acid and water, dried ($CaCl_2$), and fractionated from a small piece of sodium. The pure bromide (130 g., 52%) had b. p. 48°, n_D^{20} 1·4438 (Farrell and Bachmann [15] give b. p. 48°, n_D^{20} 1·4426). No 2-bromopropene was obtained on reaction of the dibromo-acid with sodium carbonate.

2-Bromopropene (11 g.) was added in one lot to a stirred suspension of finely divided lithium (1 g.) in anhydrous ether (200 ml.). Reaction set in within 1 min. and the solvent refluxed without external heating. After 30 min., all the metal had been consumed.

α-*Methylacrylic Acid.*—*iso*Propenyl-lithium (from Li, 1 g.) in ether was added to a large excess of powdered carbon dioxide. The mixture was allowed to attain room temperature, water was added, and the solution was acidified with hydrochloric acid. The ether layer was separated and extracted with 2N-sodium carbonate. Evaporation of the ether gave only 0·2 g. of material which did not form a 2 : 4-dinitrophenylhydrazone and was not further investigated. The alkaline extract was acidified with concentrated hydrochloric acid and extracted with ether, and the ether extract was dried (Na_2SO_4) and distilled, giving α-methylacrylic acid (1·3 g., 17%), b. p. 65°/11 mm., n_D^{24} 1·4292 (lit.,[16] b. p. 72°/14 mm., n_D^{20} 1·4314). The acid was characterised as the *benzylamine salt* which crystallised from ethyl acetate in needles, m. p. 93—94°, undepressed on admixture with a sample from authentic acid (Found: C, 68·4; H, 8·0; N, 7·3. $C_{11}H_{15}O_2N$ requires C, 68·4; H, 7·8; N, 7·3%).

2-*Methyl*-1-*phenylallyl Alcohol* (2-*Methyl*-1-*phenylprop*-2-*en*-1-*ol*) (I).—Benzaldehyde (8 g.) in ether (25 ml.) was added dropwise to a stirred ethereal solution of *iso*propenyl-lithium (from Li, 1 g.) at room temperature. After 1 hr., excess of saturated aqueous ammonium chloride was added and the ether layer was separated, dried (Na_2SO_4–K_2CO_3), and distilled, giving the *alcohol* (8 g., 72%), b. p. 55°/0·1 mm., n_D^{22} 1·5349, $\lambda_{max.}$ 2510 (ε 500) and 2580 Å (ε 400) in EtOH (Found: C, 80·9; H, 8·2. $C_{10}H_{12}O$ requires C, 81·0; H, 8·2%).

α-*Methylcinnamyl Alcohol* (2-*Methyl*-3-*phenylprop*-2-*en*-1-*ol*) (VII).—The foregoing alcohol (2 g.) was refluxed with 0·1M-hydrogen chloride in 60% aqueous acetone (100 ml.) for 20 hr. The solution was neutralised with potassium carbonate, and the acetone was distilled off. Isolation of the product with ether gave the alcohol (1 g., 50%), b. p. 77°/0·1 mm., n_D^{22} 1·5650,

* The authors cited give severally $\lambda_{max.}$ 2230, 2310, and 2410 Å. These differences may perhaps be due to ring–chain tautomerism with 1-vinyl*cyclo*butene.

[11] Blomquist and Verdol, *J. Amer. Chem. Soc.*, 1955, **77**, 81; 1956, **78**, 109; Bailey and Economy, *ibid.*, p. 1133; Bailey, Cunov, and Nicholas, *ibid.*, p. 2787.
[12] Booker, Evans, and Gillam, *J.*, 1940, 1453.
[13] Newman and Deno, *J. Amer. Chem. Soc.*, 1951, **73**, 3644.
[14] Koch, *J.*, 1949, 408.
[15] Farrell and Bachmann, *J. Amer. Chem. Soc.*, 1935, **57**, 1281.
[16] Brühl, *Annalen*, 1880, **200**, 181; Autenrieth and Pretzell, *Ber.*, 1903, **36**, 1272.

$\lambda_{max.}$ 2440 Å (ε 13,500) in EtOH (Found : C, 80·8; H, 8·4%) (Li and Eliott[17] give b. p. 96°/1·5 mm.).

Oxidation of the alcohol (0·5 g.) with tetrachloro-1 : 2-benzoquinone in chloroform at room temperature and treatment of the product with Brady's reagent gave α-methylcinnamaldehyde 2 : 4-dinitrophenylhydrazone (0·74 g., 67%), m. p. 209—210°, $\lambda_{max.}$ 3900 Å (ε 42,000) in $CHCl_3$.

1 : 2-*Dimethyl*-1-*phenylprop*-2-*en*-1-*ol* (II).—Acetophenone (8 g.) in ether (25 ml.) was allowed to react with *iso*propenyl-lithium (from Li, 1 g.), and the product was worked up as above, giving the *alcohol* (9·5 g., 88%), b. p. 58°/0·1 mm., n_D^{22} 1·5300, $\lambda_{max.}$ 2440 Å (ε 500) in EtOH (Found : C, 81·5; H, 8·8. $C_{11}H_{14}O$ requires C, 81·4; H, 8·7%).

αβ-*Dimethylcinnamyl Alcohol* (2 : 3-*Dimethyl*-3-*phenylprop*-2-*en*-1-*ol* (VIII) and 2-*Methyl*-3-*phenylbuta*-1 : 3-*diene* (X).—The foregoing alcohol (3·5 g.) was refluxed for 12 hr. with 0·005M-hydrogen chloride in 60% aqueous acetone (100 ml.). Isolation of the products as above and fractionation gave the *diene* (1·8 g., 60%), b. p. 39—41°/0·1 mm., n_D^{22} 1·5380, $\lambda_{max.}$ 2230 Å (ε 10,000) in EtOH [Found : C, 90·3; H, 8·4. $C_{11}H_{12}$ requires C, 91·7; H, 8·3% (low carbon values have been obtained [18] in analogous cases)], and the *alcohol* (0·8 g., 23%), b. p. 79—81°/0·1 mm., n_D^{22} 1·5450, $\lambda_{max.}$ 2350 Å (ε 5000) in EtOH (Found : C, 81·8; H, 8·8. $C_{11}H_{14}O$ requires C, 81·4; H, 8·7%).

When the alcohol (II) was refluxed with 0·1M-hydrogen chloride–60% aqueous acetone for 20 hr., only the diene (84%) was obtained.

2-*Methyl*-1 : 1-*diphenylallyl Alcohol* (2-*Methyl*-1 : 1-*diphenylprop*-2-*en*-1-*ol*) (III).—Benzophenone (10 g.) in ether (25 ml.) was allowed to react with *iso*propenyl-lithium (from Li, 0·8 g.) and the product worked up as above, giving the *alcohol* (8 g., 65%), b. p. 80—82° (bath-temp.)/10^{-3} mm., n_D^{23} 1·5849, $\lambda_{max.}$ 2580 Å (ε 400) in EtOH (Found : C, 86·1; H, 7·6. $C_{16}H_{16}O$ requires C, 85·7; H, 7·2%).

α-*Methyl*-β-*phenylcinnamyl Alcohol* (2-*Methyl*-3 : 3-*diphenylprop*-2-*en*-1-*ol*) (IX).—The foregoing alcohol (3 g.) was heated under reflux for 20 hr. with 0·1M-hydrogen chloride–60% aqueous acetone (100 ml.). Isolation of the product as above and fractionation gave the alcohol (2·5 g., 83%), m. p. 59—60°, b. p. 126°/10^{-2} mm., n_D^{24} 1·6067. After one recrystallisation from light petroleum (b. p. 40—60°), the alcohol had m. p. 69—70°, $\lambda_{max.}$ 2420 Å (ε 14,000) in EtOH (Found : C, 85·7; H, 7·3%). (Ziegler and Tiemann [8] give b. p. 184°/11 mm., m. p. 68—69°.) The α-*naphthylurethane* crystallised from light petroleum in needles, m. p. 99—100° (Found : C, 82·5; H, 6·3; N, 3·6. $C_{27}H_{23}O_2N$ requires C, 82·4; H, 5·9; N, 3·6%).

2-*Methylpenta*-1 : 4-*dien*-3-*ol* (IV).—Acraldehyde (5 g.) in ether (25 ml.) was added to *iso*propenyl-lithium (from Li, 1 g.) at 0°. After 1 hr. at 0°, excess of aqueous ammonium chloride was added and the product isolated with ether, giving the *alcohol* (2·0 g., 23%), b. p. 47°/12 mm., n_D^{23} 1·4505, ε <100 between 2000 and 4000 Å (Found : C, 72·9; H, 10·6. $C_6H_{10}O$ requires C, 73·4; H, 10·3%).

2-*Methylhexa*-1 : 4-*dien*-3-*ol* (V).—Crotonaldehyde (7 g.) was added to *iso*propenyl-lithium, and the product was worked up as above, giving the *alcohol* (4·2 g., 38%), b. p. 58—60°/12 mm., n_D^{20} 1·4575, ε <100 between 2000 and 4000 Å (Found : C, 74·7; H, 10·9. $C_7H_{12}O$ requires C, 74·95; H, 10·8%).

2 : 3 : 5-*Trimethylhexa*-1 : 4-*dien*-3-*ol* (VI).— Mesityl oxide (8 g.) in ether (25 ml.) was treated with *iso*propenyl-lithium, and the product was worked up as above, giving the *alcohol* (8·5 g., 74%), b. p. 63°/11 mm., n_D^{22} 1·4628, ε <100 between 2000 and 4000 Å (Found : C, 77·4; H, 11·6. $C_9H_{16}O$ requires C, 77·1; H, 11·5%).

1 : 1-*Diethoxy*-2 : 3-*dimethylbut*-3-*en*-2-*ol*.—1 : 1-Diethoxyacetone (40 g.) in ether (50 ml.) was treated with *iso*propenyl-lithium (from Li, 5 g.) in ether (500 ml.) at room temperature. After 3 hr., excess of ammonium chloride was added and the ether layer was separated, dried, (Na_2SO_4–K_2CO_3), and distilled, giving the *acetal* (18 g., 35%), b. p. 89°/11 mm., n_D^{21} 1·4370 (Found : C, 64·1; H, 10·7. $C_{10}H_{20}O_3$ requires C, 63·8; H, 10·6%). Shaking the acetal (10 g.) with 2% aqueous tartaric acid for 14 hr. at room temperature gave unchanged acetal (3·2 g.) and 2-*hydroxy*-2 : 3-*dimethylbut*-3-*en*-1-*al* (2·7 g.), b. p. 69—72°/12 mm., n_D^{22} 1·4392, $\lambda_{max.}$ 3020 Å (ε 570) (Found : C, 63·2; H, 8·8. $C_6H_{10}O_2$ requires C, 63·1; H, 8·8%).

Reaction of iso*Propenyl-lithium with Dimethylformamide*.—Dimethylformamide (7 g.) in ether (25 ml.) was added dropwise to *iso*propenyl-lithium (from Li, 1 g.) in ether (200 ml.) at 0°. After 1 hr. at 0°, excess of ammonium chloride was added, the ether layer was dried (Na_2SO_4), and the solvent distilled off through an 8" column. The residue (1 ml.) gave a positive

[17] Li and Elliott, *J. Amer. Chem. Soc.*, 1952, **74**, 4089.
[18] Braude, Jones, and Stern, *J.*, 1947, 1087.

test with Schiff's reagent and on treatment with Brady's reagent furnished an unidentified 2 : 4-*dinitrophenylhydrazone* (0·4 g.) which crystallised from ethyl acetate in red needles, m. p. 198°, $\lambda_{max.}$ 3900 Å (ε 31,000) in $CHCl_3$ (Found : C, 53·5; H, 5·1; N, 19·3. $C_{13}H_{14}O_4N_4$ requires C, 53·8; H, 4·9; N, 19·3%).

Grateful acknowledgment is made to the Department of Scientific and Industrial Research for a Maintenance Grant (to E. A. E.).

Department of Chemistry, Imperial College of Science and Technology, South Kensington, London, S.W.7. [*Received, March* 14*th*, 1956.]

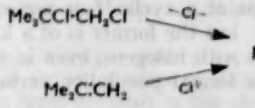
---

649. *The Kinetics and Mechanisms of Addition to Olefinic Substances. Part III.* The Carbonium Ionic Intermediate involved in Addition of Hypochlorous Acid to* iso*Butene.*

By P. B. D. de la Mare and Adib Salama.

Addition of hypochlorous acid to *iso*butene in water gives mainly 1-chloro-2-methylpropan-2-ol; the chief olefinic by-product is 3-chloro-2-methylpropene. The latter olefin is also the predominant by-product in the hydrolysis in water of 1 : 2-dichloro-2-methylpropane. Evidence is presented to support the view that these reactions proceed in substantial part through a common carbonium ionic intermediate. The reaction of *iso*butyraldehyde with phosphorus pentachloride gives a mixture of 1 : 2- and 1 : 1-dichloro-2-methylpropane. The properties of the latter substance are properly established for the first time.

Although the properties and reactions of alkyl carbonium ions have received considerable study, little is established concerning halogen-substituted carbonium ions. These substances are commonly considered to be intermediates both in heterolytic (S_N1) nucleophilic displacements involving 1 : 2-dihalides, and in reactions of olefins with donors of electrophilic halogen. The unimolecular hydrolysis of 1 : 2-dichloro-2-methylpropane and the addition of hypochlorous acid to *iso*butene should both give the same carbonium ion, and therefore the two reactions, if carried out in the same environment, should, on this view, give the same products, provided that the carbonium ion has sufficient life in solution to enable it to attain its equilibrium conformation before reaction is completed :



It is difficult to be sure, by study of the literature, what are the primary products of hydrolysis of 1 : 2-dichloro-2-methylpropane. It is known to be possible to obtain 1-chloro-2-methylpropan-2-ol in up to about 50% yield by direct hydrolysis at 70—80°, the solution being kept neutral or very slightly alkaline during the process.[1] More prolonged hydrolysis, with potassium carbonate, is known to carry the reaction through to 2-methylpropane-1 : 2-diol,[2] and, when sodium hydrogen carbonate is used, the main olefinic by-product is stated to be 1-chloro-2-methylpropene.[3] There have been various reports that, under some conditions, hydrolysis of this dichloride can give *iso*butyraldehyde. The formation[4] of the latter substance during the catalytic hydrolysis of 1 : 2-dichloro-2-methylpropane

* Part II, *J.*, 1954, 3990.

[1] Sparks and Nelson, *J. Amer. Chem. Soc.*, 1936, **58**, 1010.
[2] Pogorshelski, *J. Russ. Phys. Chem. Soc.*, 1904, **36**, 1129 (*Chem. Zentr.*, 1905, **76**, 1, 667).
[3] Dobryanski, Gutner, and Shchigelskaya, *J. Gen. Chem.* (*U.S.S.R.*), 1937, **7**, 1315 (*Chem. Abs.*, 1937, **31**, 6189).
[4] Hersh and Nelson, *J. Amer. Chem. Soc.*, 1936, **58**, 1631.

in the vapour phase at 350° could reasonably be attributed to rearrangement of the chlorohydrin [5] or diol [6] formed initially by direct hydrolysis; and this seems also to be the view adopted [4] in regard to the hydrolysis in the liquid phase at temperatures below 100°, which is reported [4,7] also to give *iso*butyraldehyde.

A number of workers have recorded [8,9] that addition of hypochlorous acid, or of chlorine water, to *iso*butene gives, in yields of 50% and upwards, the α-chlorohydrin, 1-chloro-2-methylpropan-2-ol. Michael and Leighton [9] obtained also, as a by-product in this reaction, a dichloro-*tert.*-butyl alcohol, which they considered to be formed by direct chlorination of the chlorohydrin.

Chlorination of gaseous *iso*butene with gaseous chlorine has been the subject of considerable enquiry. The main reaction is a substitution, and the main olefinic product is 3-chloro-2-methylpropene.[10] The reaction, as it is ordinarily carried out, appears to proceed in a liquid film formed by the products of the reaction, or on the surface of a catalyst if one is provided. Under conditions favourable for the minimisation of secondary reactions, the product-composition is as follows: 3-chloro-2-methylpropene, 87%; 1-chloro-2-methylpropene, 3%; 1 : 2-dichloro-2-methylpropane, 6%; and secondary products, 4%. Reeve, Chambers, and Prickett [11] have shown, by labelling $C_{(1)}$ of *iso*butene with ^{14}C, allowing chlorination to take place, and examining the position of labelling in the resulting 3-chloro-2-methylpropene, that most of the entering chlorine is attached, in the latter product, to what was $C_{(1)}$ in the original olefin.

It has generally been considered, therefore,[12] that this type of substitutive chlorination of olefins involves a carbonium ionic intermediate, which can undergo further reaction in a variety of ways, *e.g.*:

$$Me_2C{:}CH_2 + Cl_2 \xrightarrow[-Cl^-]{} Me_2\overset{+}{C}{\cdot}CH_2Cl \longrightarrow \begin{cases} Me_2C(Cl){\cdot}CH_2Cl & (6\%) \\ Me_2C{:}CHCl & (3\%) \\ CH_2{:}C(Me){\cdot}CH_2Cl & (87\%) \end{cases}$$

This scheme does not, however, appear to provide an adequate explanation of the preponderance of allylic over vinylic chloride in the product. A statistical factor of 3 : 1 should, it is true, favour the former product; but there seems to be no reason why the product ratio should exceed this value. The assumption made by Taft,[12] that the proton will be lost preferentially from the carbon atom which is the most electron-rich, because the double bond will be formed preferentially between the carbonium centre and the most electron-rich carbon atom, seems to the authors as is developed later, to neglect proper consideration of the availability of electrons in the transition state for decomposition of the carbonium ion. Synchronous mechanisms of a cyclic [13] or non-cyclic [14] type have been proposed, and avoid the above difficulty, but the former is of a kind not commonly encountered in reactions of olefinic substances with halogens, even in systems favourable to its operation; [15] and the latter, though a formal possibility, certainly needs further evidence before it could be accepted.

The purpose of the present investigation has been to examine the addition in water of hypochlorous acid to *iso*butene under conditions in which it could reasonably be assumed that a carbonium ionic intermediate is formed, giving particular attention to the products of elimination from the carbonium ion. The kinetics and mechanism of the hydrolysis,

[5] Harvey, Riggs, and Stimson, *J.*, 1955, 3267.
[6] Nevole, *Ber.*, 1876, **9**, 448.
[7] Groll and Kautter, U.S.P. 2,042,225; *Chem. Abs.*, 1936, **30**, 4872; Newlin, Thesis, Purdue Univ., 1932, see ref. 4.
[8] Henry, *Compt. rend.*, 1906, **142**, 494; *Rec. Trav. chim.*, 1907, **26**, 142; Krassusky, *J. prakt. Chem.*, 1907, **75**, 238; Moureau and Dode, *Bull. Soc. chim. France*, 1937, **4**, 286.
[9] Michael and Leighton, *Ber.*, 1906, **39**, 2157.
[10] Burgin, Engs, Groll, and Hearne, *Ind. Eng. Chem.*, 1939, **31**, 1413.
[11] Reeve, Chambers, and Prickett, *J. Amer. Chem. Soc.*, 1952, **74**, 5369.
[12] Taft, *ibid.*, 1948, **70**, 3364.
[13] Arnold and Lee, *ibid.*, 1953, **75**, 5396.
[14] Turner and Harris, "Organic Chemistry," Longmans Green & Co., London, 1952, p. 166.
[15] Mislow and Hellman, *J. Amer. Chem. Soc.*, 1951, **73**, 244.

in water, of 1 : 2-dichloro-2-methylpropane, have also been studied in order to establish whether the carbonium ion from this dichloride undergoes elimination to give the same mixture of olefins. To be certain that *iso*butyraldehyde is not a primary product of this reaction, it has proved necessary to establish the properties of 1 : 1-dichloro-2-methylpropane.

Experimental

(a) *1 : 1-Dichloro-2-methylpropane.*—1 : 1-Dichloro-2-methylpropane is formed, together with other products, in the gas-phase chlorination of *iso*butane or *iso*butyl chloride;[16,17] but it is difficult to separate this compound from its isomer, 1 : 2-dichloro-2-methylpropane, which is also formed in the same reaction. The only other method which has been used in the preparation of this *gem.*-dichloride is the reaction between *iso*butyraldehyde and phosphorus pentachloride.[18] In the present work, best yields of crude dichloride were obtained in the following way. *iso*Butyraldehyde (100 g.) was added gradually to powdered phosphorus pentachloride (350 g.) with stirring, at $<0°$. The mixture was left overnight at room temperature; it was then added gradually to ice-cold water. Extraction with pentane, followed by fractionation, gave an oil (48 g.), b. p. 102—115°/764 mm., n_D^{25} 1·4323. The following shows the rate of development of acid from this material. Samples (*ca.* 0·04 g.) were weighed into ampoules which were then cooled to $-80°$. Water (50 ml.; sufficient to form a homogeneous solution at the temperature of the reaction) was added, and the ampoules were sealed and placed in a thermostat at 45°; after appropriate times the ampoules were opened, and the contents were titrated with standard alkali to methyl-red.

Time (hours)	2·0	6·0	12·0	24·0	72·0	96·0
Total Cl (%) hydrolysed	1·6	5·1	6·6	15·0	22·0	22·4

It can be seen that reaction had nearly ceased when 22% of chlorine had been liberated from the chloride. The rate of liberation of chloride was such that it was suspected that the reaction mixture contained also 1 : 2-dichloro-2-methylpropane. Hence the mixture of chlorides (95 g., from two such experiments) was mechanically stirred with 3·5 l. of water at 45°. Samples of the clear aqueous layer were removed at intervals for titration with alkali. When the initial hydrolysis was nearly complete (after *ca.* 35 days), the material was cooled and extracted with pentane. The pentane extract was washed with sodium hydrogen carbonate solution, then with water, dried (Na_2SO_4), and carefully fractionated. There were obtained 6 g. of material, b. p. 108—110°/763 mm.,* n_D^{25} 1·4330 (Found: C, 37·9; H, 6·4. Calc. for $C_4H_8Cl_2$: C, 37·8; H, 6·35%). This material hydrolysed negligibly slowly in water at 45° (less than 1% in 45 hr.). At 100°, hydrolysis occurred slowly, and after 100 hr., the aqueous product gave with 2 : 4-dinitrophenylhydrazine a crystalline precipitate, in 30% yield based on the weight of dichloride taken. The precipitate, after crystallisation from aqueous ethanol, had m. p. 179°, and did not depress the m. p. of *iso*butyraldehyde 2 : 4-dinitrophenylhydrazone, m. p. 178—179°.

Reaction of *iso*butyraldehyde with phosphorus pentachloride in *m*-xylene gave smaller yields (*ca.* 15%) of a similar mixture of dichlorides. Reaction in pyridine gave negligible yields. The aqueous layer obtained in the above experiment after partial hydrolysis of the mixture of dichlorides was, after extraction with pentane as described, saturated with sodium chloride and extracted with ether. The ether-extract was washed with water, dried (Na_2SO_4), and fractionally distilled. There were obtained 17 g. of oil, b. p. 126·5°/761 mm., n_D^{25} 1·4368 (Found: C, 44·8; H, 8·4; Cl, 32·4. Calc. for C_4H_9OCl: C, 44·3; H, 8·4; Cl, 32·7%). This was therefore 1-chloro-2-methylpropan-2-ol derived from the 1 : 2-dichloro-2-methylpropane; an authentic specimen prepared by Henry's method[6] from methylmagnesium bromide and ethyl monochloroacetate had b. p. 70—71°/100 mm., 126°/760 mm., n_D^{25} 1·4366.

(b) *Hydrolysis of 1 : 2-Dichloro-2-methylpropane.*—(i) *Kinetics of liberation of acid.* 1 : 2-Dichloro-2-methylpropane was prepared as described by Rogers and Nelson[19] by the photochemical chlorination of *tert.*-butyl chloride. Careful fractionation gave a product, b. p. 59—60°/151 mm., 106°/760 mm., n_D^{25} 1·4346. A sample prepared by McBride and Beachell's

* Thus this dichloride actually has a b. p. higher than that of the 1 : 2-isomer.

[16] Hass, McBee, and Weber, *Ind. Eng. Chem.*, 1935, **27**, 1190.
[17] Hass and McBee, U.S.P. 2,004,072.
[18] Oeconomides, *Bull. Soc. chim. France*, 1881, **35**, 498.
[19] Rogers and Nelson, *J. Amer. Chem. Soc.*, 1936, **58**, 1028.

method [20] was kindly given to us by Mr. J. B. Ley for comparison, and was found to have identical properties and rate of hydrolysis.

The following results show the rate of hydrolysis of this dichloride in initially neutral solution. The technique has already been described. Values of the first-order velocity coefficients, here and elsewhere except where otherwise stated, have been calculated by using the formula $k_1 = 2{\cdot}303 \log_{10} \{a/(a-x)\}/t$, where a is the initial *molarity* of organic chloride and x is the molarity of chloride released at time t. Initial values, therefore, represent the initial rate of production of the first equivalent of chloride.

Time (min.)	120	240	480	720	960	1200	1680	2160	2400	2640
Total Cl (%) hydrolysed	5·1	9·6	18·9	24·8	31·6	36·4	43·2	48·1	45·1	48·4
10^3k_1 (min.$^{-1}$)†	0·90	0·89	0·99	0·95	1·04	1·08	1·18	1·51	0·97	1·30

The initial rate-coefficient at 45° is, therefore, $0{\cdot}90 \times 10^{-3}$ min.$^{-1}$; it rises gradually through the course of the reaction, since, as will be seen below, the products gradually undergo further reaction, liberating finally rather more than one equivalent of chloride.

The following shows the course taken by the hydrolysis in initially alkaline solution, with 0·0048M-dichloride and 0·0048M-sodium hydroxide. The reaction was followed by titration with standard acid until 50% of the total chlorine in the dichloride had been liberated; then by titration with standard alkali.

Time (min.)	120	240	360	480	840	960	1080	1440	2160	3840	4320
Total Cl (%) hydrolysed	7·7	16·5	24·4	32·1	46·4	48·9	54·5	61·5	66·3	70·9	70·9
10^3k_1 (min.$^{-1}$)†	0·73	0·82	0·86	0·89	0·84	0·79	—	—	—	—	—

The rate-coefficient, at 45°, has the mean value * $k_1 = 0{\cdot}82 \times 10^{-3}$ min.$^{-1}$; reaction proceeds substantially beyond the liberation of one equivalent of chloride.

(ii) *The liberation of olefin.* This was followed in the following way. Ampoules containing 75 ml. of the reaction mixture were removed from the thermostat and cooled. Portions (10 ml.) were removed for titration with standard alkali. To the remainder was added excess of aqueous bromine solution (*ca.* 0·02N in sodium bromide solution). The mixture was shaken and left for 1 hr., and was then treated with excess of potassium iodide and titrated with standard sodium thiosulphate solution to sodium–starch glycollate. Blank experiments showed that under these conditions neither 1 : 2-dichloro-2-methylpropane nor 1-chloro-2-methylpropan-2-ol consumed bromine; and that both 3- and 1-chloro-2-methylpropene reacted rapidly with bromine. The following are the results.

Time (min.)	360	900	1440	2880	4320	4820	12,960
Dichloride (g.) in 75 ml.	0·1164	0·1398	0·1282	0·1168	0·1416	0·1428	0·1459
Titre (ml. of 0·0358N-NaOH = 10 ml. of reactants)	1·00	2·25	2·80	3·65	4·50	4·70	4·95
Titre (ml. of 0·0101N-$Na_2S_2O_3$ = 65 ml. of reactants)	7·15	17·1	20·8	26·8	32·2	32·6	27·2
Total Cl hydrolysed (%)	14·3	26·7	36·3	51·8	52·7	54·6	56·3
Total olefin formed (%)	4·55	9·04	12·0	17·0	16·8	16·8	13·8
Ratio olefin/Cl^-	0·32	0·34	0·33	0·33	0·32	0·31	0·25

The gradual decrease in proportion of olefin towards the end of the reaction is the result, presumably, of slow hydration of this material under the acidic conditions prevailing.

(iii) *Estimation of 3-chloro-2-methylpropene in the olefinic mixture.* This allylic chloride is hydrolysed in water at a rate similar to that of 1 : 2-dichloro-2-methylpropane, as is shown by the following results, obtained at 45° by a technique similar to that described above.

Time (min.)	60	120	240	480	720	960	1200	1440	1680	1920	2400
Hydrolysis (%)	5·9	12·6	20·6	33·6	47·2	57·2	58·7	69·5	74·5	77·8	83·6
10^3k_1 (min.$^{-1}$)	10·1	11·2	9·6	8·5	8·9	8·8	7·4	8·2	8·1	7·8	7·5

The results are rather less satisfactory than those obtained for the dichloride, probably because the lower boiling point of the former chloride had the result that an appreciable fraction

* These values are obtained by assuming that two equivalents of chloride are released for each mole of dichloride which forms chlorohydrin (84%) and one equivalent for the remainder; for the chlorohydrin, but not the other products, will react instantaneously to liberate a further mole of hydrogen chloride. Hence the theoretical infinity value should correspond with the liberation of $(2 \times 84 + 16)/2 = 92\%$ of chloride from the dichloride.

[20] McBride and Beachell, *J. Amer. Chem. Soc.*, 1948, **70**, 2532.

of the material was always in the vapour phase. The initial rate-coefficient ($1{\cdot}0 \times 10^{-3}$ min.$^{-1}$ at 45°) is, however, considered to be correct to within 10%. The product of the reaction must be 2-methylprop-2-en-1-ol, and this is not extracted from aqueous solution by pentane, whereas the vinylic chloride (1-chloro-2-methylpropene), also produced in the hydrolysis of 1 : 2-dichloro-2-methylpropane, is not hydrolysed by water and is extracted quantitatively from water by pentane. The following method was used, therefore, for estimation of the ratio of isomeric olefins produced in the hydrolysis of 1 : 2-dichloro-2-methylpropane. Reaction was allowed to proceed, as described above, for 115 hr., which was sufficiently long to ensure complete hydrolysis of the dichloride, and substantially complete (more than 95%) hydrolysis of the 3-chloro-2-methylprop-1-ene formed in the reaction, and was not too long for any significant destruction of olefin by acid-catalysed hydration. The mixture was then cooled and extracted three times with pentane. The pentane extracts were washed three times with a little water. The residual aqueous solution and the aqueous washings were separately treated with excess of standard bromine solution, and the olefin was determined in them as described above. Blank experiments showed (*a*) that, with 3-chloro-2-methylpropene after this treatment for 72 hr., 95% of olefinic material was in the aqueous fractions; and (*b*) that with 1-chloro-2-methylpropene, no olefinic material remained in the aqueous solution after extraction with pentane. The following are results of a typical experiment. The water-soluble olefinic material in the aqueous residue and washings, after treatment of 0·0810 g. of 1 : 2-dichloro-2-methylpropane with water at 45° for 115 hr., used up bromine equivalent to 12·7 ml. of 0·0102N-sodium thiosulphate. Hence there was produced in the reaction 10·2% of 3-chloro-2-methylpropene. The remainder of the olefinic material, being unhydrolysed by water and extracted from water by pentane, is presumably 1-chloro-2-methylpropene.

A similar technique was used for the estimation of 2-methylprop-2-en-1-ol in the olefinic product obtained in alkaline solution. In this case, reaction with 0·1N-sodium hydroxide was complete in 45 hr., and the percentage of total olefinic material in the aqueous hydrolysate was 34%, calculated on the weight of dichloride taken. This value was reduced to 6·2% when the aqueous solution had first been extracted with pentane to remove 1-chloro-2-methylprop-1-ene.

(iv) *Estimation of isobutyraldehyde.* 1 : 2-Dichloro-2-methylpropane (1·7 g.) was dissolved in 3 l. of an aqueous solution of 2 : 4-dinitrophenylhydrazine (0·03% in 0·7N-hydrochloric acid). The solution was kept at 45° for 48 hr. After cooling, filtration gave 0·06 g. of a yellow precipitate, which, after crystallisation from dilute ethanol, had m. p. 175° and did not depress the m. p. of an authentic specimen of *iso*butyraldehyde 2 : 4-dinitrophenylhydrazone, m. p. 178—179°. The maximum amount of *iso*butyraldehyde obtained under these strongly acidic conditions is therefore 1·7%, and this material is probably derived (cf. ref. 4) from the acid-catalysed rearrangement of one of the products of reaction. Under less strongly acidic conditions, *iso*butyraldehyde appears to be absent from the products of hydrolysis. We are indebted to Mr. J. B. Ley for polarographic examination of aqueous solutions obtained by heating 1 : 2-dichloro-2-methylpropane (1 g.) with 1 l. of water at 45° for up to 200 hr. No *iso*butyraldehyde was detected at any stage in the hydrolysis.

(v) *Isolation of 1-chloro-2-methylpropan-2-ol.* In a 100 l. flask provided with a stirrer and a glass-jacketed immersion heater, 50 g. of 1 : 2-dichloro-2-methylpropane were stirred with 90 l. of water for 48 hr., the temperature being maintained at 45° ± 2°. The mixture was cooled to room temperature. Air was bubbled through the solution, dried by passage through calcium chloride, and passed through traps cooled in liquid air; no volatile material was condensed. The solution was saturated with ether and then with sodium sulphate. The ether layer was removed, and the aqueous solution was further extracted with 20 l. of ether. The combined ether extracts were dried (Na_2SO_4) and fractionated, giving 23 g. (*ca.* 56% yield) of crude product, b. p. 63—72°/101 mm., of which a middle fraction (10 g.) had the following properties: b. p. 71—72°/101 mm., n_D^{25} 1·4367 (Found: C, 44·1; H, 8·4; Cl, 32·8. Calc. for C_4H_9OCl: C, 44·3; H, 8·4; Cl, 32·7%).

The rate of hydrolysis of this material was followed in alkaline solution. Known volumes of solutions of the chlorohydrin and of sodium hydroxide were mixed at 0°, and 5 ml. samples were pipetted at intervals into chilled acetone containing excess of standard hydrochloric acid, and were then back-titrated with alcoholic sodium hydroxide to lacmoid. Under these conditions the end-point was stable, and the product (*iso*butene oxide) did not react with the quenching acid. For initial concentrations of chlorohydrin and alkali respectively 0·03186N and 0·07066N, the second-order rate-coefficient (mean, 10·6 l. mole^{-1} min.$^{-1}$) was substantially constant over 80% reaction. The experimental titration at completion of the reaction agreed with that calculated within 5%. This rate-coefficient is almost identical with that (10·7

l. mole^{-1} min.$^{-1}$) obtained independently by Mr. P. Ballinger in these laboratories using a sample of authentic 1-chloro-2-methylpropan-2-ol, b. p. 70—71°/100 mm., 126°/760 mm., n_D^{25} 1·4366, prepared by one of us (A. S.) from the reaction of ethyl monochloroacetate with methylmagnesium bromide as described by Henry.[8]

The fractions of lower b. p. contained olefinic substances, but we did not succeed in isolating a pure material from these.

(c) *Addition of Hypochlorous Acid to* iso*Butene.*—(i) *Isolation of* 1-*chloro*-2-*methylpropan*-2-*ol.* *iso*Butene was bubbled into *ca.* 80 l. of water maintained at 45° ± 2°. Standardised aqueous hypochlorous acid (2 l.; *ca.* 0·2M) was added at such a rate that the concentration of hypochlorous acid was always below 0·001M. After completion of the reaction, the products were isolated as described above. Fractionation gave an unsaturated fraction (2·4 g.), b. p. 40—122°, n_D^{25} 1·4135, followed by a main fraction (27 g.), b. p. 123—125°/755 mm., n_D^{25} 1·4367. Refractionation of this gave a material, b. p. 125—126°, n_D^{25} 1·4361; there was no sign of the presence of any material of higher b. p.

The mean rate-coefficient for the reaction of this material (0·03089N) with sodium hydroxide (0·07066N) at 0° was 10·6 l. mole^{-1} min.$^{-1}$, in good agreement with that recorded above for material obtained by hydrolysis of 1 : 2-dichloro-2-methylpropane.

(ii) *Estimation of* 3-*chloro*-2-*methylpropene.* Excess of *iso*butene, in a fragile bulb, was placed in a Pyrex tube containing 500 ml. of standardised dilute aqueous hypochlorous acid (*ca.* 0·001M). The tube was sealed, and the bulb was broken by shaking. The tube was placed in a thermostat at 45° for *ca.* 120 hr., to ensure hydrolysis of any 3-chloro-2-methylpropene. The reaction mixture was then cooled to room temperature and extracted three times with pentane, to remove both excess of *iso*butene and any 1-chloro-2-methylpropene. Olefinic material was then estimated in the aqueous residue, by the method described above. The mean of three values for the percentage of 3-chloro-2-methylpropene, based on the amount of hypochlorous acid consumed, was 11·7%.

The above method could not conveniently be used for determination of 1-chloro-2-methylpropene; and it was considered desirable to obtain an independent estimation of 3-chloro-2-methylpropene. The following method, involving isotopic dilution, was adopted. Aqueous hypochlorous acid enriched with radioactive chlorine was prepared by adding N-H^{36}Cl (7 ml.; activity 15 microcuries) to 70 ml. of 0·27M-hypochlorous acid. A portion was retained for reference. It had a specific activity of 2·38 × 10^6 (units: counts per min./concn.); this figure represents the result of determining in a Geiger tube, used for all the measurements recorded in this paper, the number of counts per minute (in this case, 766) corrected for the small background, of a solution of known concentration (in this case, 0·00321M). *iso*Butene was bubbled into water (5 l.) in a flask fitted with a ground-glass precision stirrer and a tap-funnel. It was then warmed to 45°; a sample contained *ca.* 0·003M-olefin, as measured by titration with standard bromine solution. A slow stream of *iso*butene was bubbled through this aqueous solution, to ensure an excess of this material, while 50 ml. of 0·26M-HO^{36}Cl solution were added at such a rate that the concentration of hypochlorous acid did not exceed 0·001M. The reaction mixture was, after completion of the reaction, cooled to 0°. A mixture of 10·38 g. of pure inactive 3-chloro-2-methylpropene and 11·89 g. of 1-chloro-2-methylpropene dissolved in ethanol (150 ml.) was added, and stirred with the aqueous solution of the products for 3 hr. to ensure complete mixing of the materials. It was then extracted with pentane (1·6 l.). The pentane extract was dried (Na_2SO_4) and fractionally distilled, giving a fraction, F_1 (4·3 g.), b. p. 65—73°/764 mm., n_D^{25} 1·4142 (hydrolysable Cl, 38·1%; specific activity, 1511). This was a mixture of the isomeric 1- and 3-chloro-2-methylpropenes, containing also a trace of 1-chloro-2-methylpropan-2-ol, and separate portions were treated in the following ways: (*A*) Fraction F_1 (2·97 g.) was heated at 45° for 17 hr. with 55 ml. of N-sodium ethoxide. Water was then added, and the mixture was extracted with pentane. The sodium chloride recovered from the residue had specific activity 3075; this gives a slightly high estimate of the specific activity of the 3-chloro-2-methylpropene, since it contains a little chloride derived from 1-chloro-2-methylpropan-2-ol. The pentane extract was dried and fractionated; there were recovered 1·03 g., b. p. 68—75°, n_D^{25} 1·4050 (hydrolysable Cl, 5·7; total Cl, 21·4%; specific activity, 386 based on total Cl). (*B*) Fraction F_1 (1·21 g.) was refluxed in 75% ethanol containing 0·1N-sodium hydroxide (5 ml.) for 1 hr., and the mixture was then distilled. The residue of sodium chloride (R_1) had specific activity 9038; this high value results from the presence of a trace of the main product of the reaction, 3-chloro-2-methylpropan-2-ol, which, being undiluted, has very high specific activity. The distillate, from which this material had now been removed completely, was refluxed with alkali, added in 1 ml. portions (sufficient to keep the mixture

continually alkaline to lacmoid added as indicator) for *ca.* 6 hr., and the mixture was then again distilled. The residue of sodium chloride, R_3, had specific activity 2863. The distillate was treated again in a similar way, and the residue, R_4, had specific activity 2760. Thus the chloride released on hydrolysis in residues R_3 and R_4 was of uniform specific activity, within the limits of experimental and statistical error, and it is assumed that this represents the specific activity of the diluted 3-chloro-2-methylpropene.

From the given specific activities, the weights of diluting materials added, and the amount of hypochlorous acid used in the reaction, the percentage of 3-chloro-2-methylpropene can be calculated as 11·9%, in good agreement with the value obtained by another method under slightly different conditions of reaction. It is clear that very much less of the isomer, 1-chloro-2-methylpropene, is produced in the reaction, since the specific activity of the organic chloride recovered in experiment (A) is very small. When corrected for the presence of hydrolysable chlorine of specific activity 2800, the amount of vinylic chloride formed in the reaction is not greater than 0·4%.

Discussion

Products of Hydrolysis of 1 : 2-*Dichloro-2-methylpropane.*—The above experiments confirm that *iso*butyraldehyde is not formed in any appreciable extent as a primary product of the hydrolysis of 1 : 2-dichloro-2-methylpropane. It can also be concluded that only the tertiary chlorine atom is concerned in the main reaction; for any hydrolysis of the primary chloride atom would give a chlorohydrin, 2-chloro-2-methylpropan-1-ol, which is known [21] to be hydrolysed very rapidly under the conditions used in the present work. In the present experiments, the course and extent of hydrolysis are quantitatively accounted for, within the experimental error, by the following scheme, in which the rate-coefficient k_1' is estimated by extrapolation, to lower temperatures, of values given by Harvey, Riggs, and Stimson.[5]

$$Me_2CCl\cdot CH_2Cl \xrightarrow{k_1} \begin{cases} Me_2C(OH)\cdot CH_2Cl\ (84\%) \xrightarrow{k_2'} Me_2C(OH)\cdot CH_2\cdot OH \\ Me_2C{:}CHCl\ (6\%) \\ CH_2Cl\cdot CMe{:}CH_2\ (10\%) \xrightarrow{k_1''} CH_2(OH)\cdot CMe{:}CH_2 \end{cases}$$

$k_1 = 0{\cdot}9 \times 10^{-3}$ min.$^{-1}$. $k_1' = 0{\cdot}003 \times 10^{-3}$ min.$^{-1}$. $k_1'' = 1{\cdot}0 \times 10^{-3}$ min.$^{-1}$.

This scheme requires that the liberation of chlorine from the dichloride (the very slow hydrolysis of the α-chlorohydrin being neglected) should be 55%, and therefore that the values of the first-order rate coefficients, calculated on the liberation of one equivalent of chlorine per mole of dichloride, should rise through the course of the reaction. The very slow [5] hydrolysis of the chlorohydrin accounts for the very slow further increase in the liberation of chloride, and in part for the ultimate formation of 2-methylpropane-1 : 2-diol recorded by Pogorshelski.[2]

Considering first the main product of reaction, 1-chloro-2-methylpropan-2-ol, there is no doubt whatever that this compound is produced in a unimolecular (S_N1) process. The initial rate of hydrolysis is not accelerated by added alkali, so that the main product must be formed in a stage in which the concentration of nucleophilic reagent is not contributing to the rate-equation; this is diagnostic of reaction by the S_N1 mechanism. In any case, so rapid a bimolecular formation of this compound from the dichloride at such moderate temperatures would be extremely improbable in this compound for steric reasons.[22]

Considering now the main olefinic product, 3-chloro-2-methylpropene, the evidence is very strong that this compound is also produced in a unimolecular process, rather than by a bimolecular ($E2$) elimination. For reactions of this compound under conditions favourable to bimolecular processes [23] give the isomeric vinylic halide, 1-chloro-2-methylpropene, which is also, as the present work shows, formed in predominant amount in alkaline solution in water.

It is clear that the vinylic olefin produced in these reactions (1-chloro-2-methylpropene)

[21] Nilsson and Smith, *Z. phys. Chem.*, 1933, **166**, *A*, 143.
[22] Dostrovsky, Hughes, and Ingold, *J.*, 1946, 173.
[23] Mouneyrat, *Ann. Chim.* (*France*), 1900, **20**, 533.

is obtained, in alkaline solution, as the result of a bimolecular (*E*2) elimination; as is also, presumably, the case in the experiments recorded by Dobryanski *et al.*,[3] who used aqueous sodium carbonate and sodium hydrogen carbonate solutions. The situation in regard to the mechanism of production of this olefinic chloride by hydrolysis in initially neutral aqueous solution cannot, however, be determined through the experiments so far discussed. It seems possible, from comparison with the orientation observed in the addition of hypochlorous acid to 2-methylpropene, that this vinylic halide, is, in part, produced in neutral or acid conditions by a bimolecular (*E*2) attack of water on the dichloride.

Two subsidary points require discussion. The first refers to the slow fall-off in measured percentage of 3-chloro-2-methylpropene on prolonged heating of the reaction mixture, as shown in the data on p. 3340. This almost certainly results from the slow acid-catalysed hydration of 3-chloro-2-methylpropene. Independent estimations, by Mr. J. B. Ley in these laboratories, of the rate of the latter process at higher temperatures, are consistent with this hypothesis; the effect is not sufficiently great to affect seriously the determination of this olefin in the reaction mixture for the first 100 hours of reaction.

The second point concerns the slight reduction in rate found when the hydrolysis of the dichloride is carried out in the presence of alkali, allowance having been made in the calculation for the instantaneous alkaline hydrolysis of the chlorohydrin. The effect is very near the limit of experimental error, but, if real, may be related to the similar reductions in rate which have been reported in the past for other systems,[24] though no comparative data have been recorded, as far as we are aware, for pure water as solvent.

Addition to iso*Butene.*—The addition of hypochlorous acid to 2-methylpropene is too rapid for kinetic examination; but the aqueous conditions used in the present work are extremely favourable for the formation of a carbonium ion; and it is assumed, by analogy with the situation which is generally accepted [25,26] for additions to other olefinic compounds, that, in the present case, attack by the hypochlorous acidium ion, H_2OCl^+, or possibly by chlorine when hydrogen chloride was present in the reaction mixture, resulted in the formation of a carbonium ion, $Me_2\overset{+}{C}\cdot CH_2Cl$.

No evidence has been found for the occurrence of any 1 : 2-shift in the further reactions of this ion. Thus 1 : 2-shift of hydrogen, giving $Me_2CH\cdot\overset{+}{C}HCl$, would result in the formation of *iso*butyraldehyde, which was not detected in the products of addition; 1 : 2-shift of hydrogen giving $^+CH_2\cdot CHMe\cdot CH_2Cl$ would result in the formation of 3-chloro-2-methylpropan-1-ol, whereas this compound has [27] b. p. 76—78°/21 mm., n_D^{25} 1·4460, both considerably higher than those (b. p. 71°/100 mm., n_D^{25} 1·4367) of the chlorohydrin actually produced in the reaction; and a 1 : 2-shift of chlorine would result in the formation of 2-chloro-2-methylpropan-1-ol, which is known [28] not to be produced in this reaction.

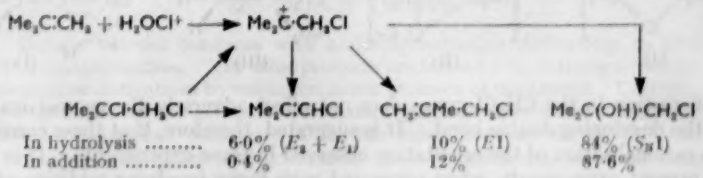
The proportion of 3-chloro-2-methylpropene, relative to the total amount of hypochlorous acid undergoing reaction, has been estimated by two methods; first, from the amount of olefinic material hydrolysable to an olefin not extracted by pentane from water, and, secondly, by isotopic dilution. The results (11·7 and 11·9% respectively) are in concordance which is probably better than the experimental reliability of the methods; they accord fairly well also with the value (10%) obtained in the hydrolysis of 1 : 2-dichloro-2-methylpropane, and this agreement would be improved if allowance were made in the latter case for the extra accompanying alternative elimination. The dichloro-*tert.*-butyl alcohol obtained in small yield by Michael and Leighton [9] is probably, therefore, 1 : 3-dichloro-2-methylpropan-2-ol, formed by addition of hypochlorous acid to 3-chloro-2-methylpropene.

The proportion of 1-chloro-2-methylpropene has been determined by isotopic dilution as being *ca.* 0·4%. This value cannot be considered very reliable, but is a maximum figure. If the determined value is accepted, then the ratio of vinylic to allylic chloride

[24] Lucas and Hammett, *J. Amer. Chem. Soc.*, 1942, **64**, 1928; Benfey, Hughes, and Ingold, *J.*, 1952, 2494.
[25] Cf. Gwyn Williams, *Trans. Faraday Soc.*, 1941, **37**, 749.
[26] Cf. de la Mare and Pritchard, *J.*, 1954, 3910, 3990.
[27] Waddle and Adkins, *J. Amer. Chem. Soc.*, 1939, **61**, 3361.
[28] Smith and Skyle, *Acta Chim. Scand.*, 1951, **5**, 1415.

formed in the ionising conditions of the present experiments is 1 : 30, in good agreement with that recorded (1 : 29) for the low-temperature chlorination of *iso*butene by chlorine under non-hydrolytic conditions.

The following scheme, therefore, represents, in our view, the reaction in water of *iso*butene with hypochlorous acid, and the hydrolysis of 1 : 2-dichloro-2-methylpropane, at 45° :



If the carbonium ion, $Me_2\overset{+}{C}\cdot CH_2Cl$, had the structure implied by this formulation, it seems likely that the direction of elimination would be controlled by factors analogous to those which control orientation in elimination from alkyl carbonium ions. Hughes, Ingold, and their co-workers [29] have established that electromeric effects of substituents control the orientation almost exclusively in such eliminations: the presence of alkyl groups which can hyperconjugate with either end of the developing double bond promotes the elimination.

In the present example, the inductive effect of the chlorine substituent must increase the ease of separation of the proton, other things being equal; and the electromeric effect of the chlorine substituent must increase the ease of double-bond formation between the attached carbon atom and the neighbouring carbonium ionic centre. Both these effects should combine * in making the formation of 1-chloro-2-methylpropene preferred, and, since this result is not found experimentally, it seems that some alternative explanation is called for.

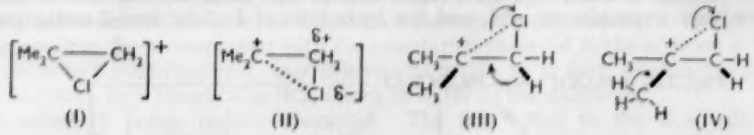
In writing the structure of such a carbonium ion in the simple way so far adopted, one important feature of the structure has been neglected, namely, the possibility of interaction between the carbonium ionic centre and the halogen. Interaction in this way was first proposed by Roberts and Kimball,[30] and the principle has been developed extensively of recent years, particularly by Winstein and his co-workers,[31] to give accounts of stereochemical and kinetic facts observed in reactions which involve carbonium ions of this type. For the present argument, it is irrelevant whether the structures are written in the "chloronium" form,[30,31] as in formula (I), in which the two carbon atoms are considered to be essentially bonded equivalently to the chlorine, or whether the intermediates are best regarded as having structures in which the interaction between the halogen and one of the carbon atoms is considered to be essentially electrostatic in character, as has been proposed in certain cases [25] (cf. formula II).

Whatever the nature of the interaction, its effect on the relative ease of loss of hydrogen from the two possible positions ought to have the observed effect on the orientation, for the following reasons. The transition state for elimination giving the vinylic halide is shown in (III); the distortion resulting from neighbouring-group interaction tends to maintain the chlorine atom of the CH_2Cl group in a position which is particularly strained relatively

* Taft's theory,[13] referred to on p. 3338, requires that the inductive effect of the chlorine substituent should, despite its acid-promoting power, diminish the relative ease of formation of a double bond with the adjacent carbonium centre, by diminishing the electron density at the carbon atom from which the proton is to be lost. This theory seems to the authors to focus attention on the electron density in the carbonium ion itself, rather than on the electron density in the carbonium ion as it undergoes proton-loss, *i.e.*, in the transition state for elimination. The whole pattern of unimolecular eliminations is one of dominant conjugative and hyperconjugative influences, and Taft's theory does not seem to fit very happily into this pattern.

[29] Dhar, Hughes, Ingold, Mandour, Maw, and Woolf, *J.*, 1948, 2093.
[30] Roberts and Kimball, *J. Amer. Chem. Soc.*, 1937, **59**, 947.
[31] Cf. Winstein, *Bull. Soc. chim. France*, 1951, **18**, C 55.

to the final positions of these atoms in the product. The transition state for the alternative elimination is shown in formula (IV). The unaffected hydrogen atoms of the CH_3 group from which elimination is occurring are able to adopt relatively unstrained positions,



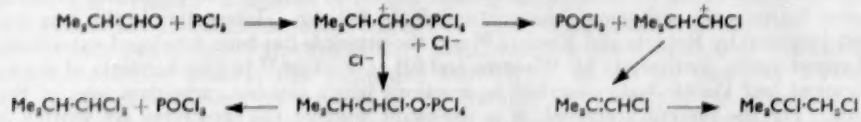
(I) (II) (III) (IV)

and the distortion in the CH_2Cl group does not affect adversely the geometrical requirements of the developing double bond. It is suggested, therefore, that these considerations provide a rationalisation of the orientation observed in these experiments. It is felt, also, that the present experiments, when compared with those involving addition of chlorine to *iso*butene under aprotic conditions, make it more certain that the latter reaction involves a carbonium ionic intermediate, despite the relatively non-ionising conditions.

The Reaction between iso*Butyraldehyde and Phosphorus Pentachloride.*—Little is known concerning the mechanism of this reaction, and, so far as the authors are aware, there have been few discussions of it. Chlorinations, by this reagent, of aliphatic aldehydes and ketones do not usually proceed in good yield, and there have been many reports (cf. refs. 18, 32) that vinylic halides are the most important by-products. Rearrangement during the reaction, to give a 1 : 2-dichloride, has not, so far as we are aware, been noted before the present work. The following route to the vinylic chloride is possible, and in the present case would allow the formation therefrom of the rearranged dichloride :

$$Me_2CH{\cdot}CHO \rightleftharpoons Me_2C{:}CH(OH);\ Me_2C{:}CH(OH) + PCl_5 \longrightarrow Me_2C{:}CHCl + HCl + POCl_3;$$
$$Me_2C{:}CHCl + HCl \longrightarrow Me_2C(Cl){\cdot}CH_2Cl$$

An alternative possibility, which takes into account the specific usefulness of phosphorus pentachloride in these chlorinations, is that shown in the scheme below :



We are greatly indebted to the Shell Group of Companies for a grant (to A. S.) which enabled this work to be completed, and to Professors C. K. Ingold, F.R.S., and E. D. Hughes, F.R.S., for their interest.

William Ramsay & Ralph Forster Laboratories,
University College, Gower St., London, W.C.1. [*Received, April 19th,* 1956.]

[32] Henne, Renoll, and Leicester, *J. Amer. Chem. Soc.*, 1939, **61**, 938.

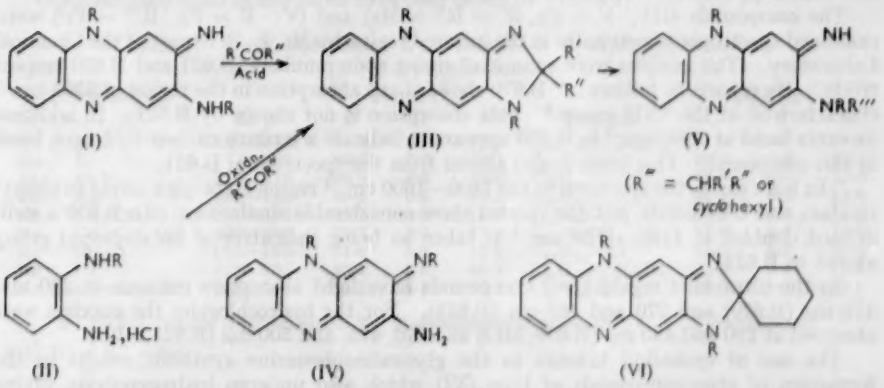
650. *The Oxidation of Derivatives of* o-*Phenylenediamine. Part IV.* A New Series of Glyoxalinophenazines derived from Anilinoaposafranines and their Behaviour on Hydrogenation.*

By Vincent C. Barry, J. G. Belton, J. F. O'Sullivan, and Dermot Twomey.

Certain ketones condense with anilino*apo*safranine derivatives to give glyoxalinophenazines. The same products are formed from suitable *o*-phenylenediamine derivatives by oxidation in the presence of the ketone. Catalytic hydrogenation of the glyoxalinophenazines yields in most cases substituted anilino*apo*safranines containing a further substituent in the N^2-position. The latter derivatives are extremely potent substances in combating experimental tuberculosis in mice.

In Part I [1] the formation of glyoxalinophenazine derivatives from anilino*apo*safranine was mentioned as a confirmation of the structure of the latter. The present paper describes the synthesis of a number of these compounds, the evidence on which their structure is based, and their behaviour on hydrogenation.

Glyoxalinophenazines may be formed by condensation of certain ketones with the anilino*apo*safranine derivatives in acid solution, preferably in syrupy phosphoric or polyphosphoric acid, or by oxidation of the corresponding 2-aminodiphenylamine salt with ferric chloride or *p*-benzoquinone in the presence of excess of ketone. With *cyclo*hexanone, acetone, and derivatives of the latter, yields were of the order of 50%, while with acetophenone and 4-acetylpyridine they were below 20%. No glyoxalinophenazine could be isolated with benzophenone, 4 : 4′-dihydroxybenzophenone, or deoxybenzoin in either synthetic method. The glyoxalinophenazines (III) are yellow to orange-red compounds which exhibit a greenish-yellow fluorescence in solution and they are formed as shown.



It is unlikely that the anilino*apo*safranines (I; R = Ph) are intermediates in the formation of the glyoxalinophenazines (III) from the *o*-phenylenediamine derivatives (II), as the glyoxalinophenazines may be obtained from compounds of type (II) in cases where oxidation of the latter in the absence of the ketone does not yield anilino*apo*safranine derivatives.[2] Further, the glyoxalinophenazines (III) are much more readily formed by the oxidation process than they are by condensation of the ketone with the anilino*apo*safranines (I). In all cases where glyoxalinophenazines (III) were obtained by oxidation of *o*-phenylenediamine derivatives, compounds of type (IV) were also produced.

The structure of the glyoxalinophenazines is based on the following facts. During the

* Part III, *J.*, 1956, 896.

[1] Barry, Belton, O'Sullivan, and Twomey, *J.*, 1956, 888.

[2] *Idem*, *J.*, 1956, 893.

condensation of anilino*apo*safranine derivatives (I) with a ketone, a molecule of water is eliminated without the production of an olefinic bond. A molecular-weight determination gave a value of **420** for the glyoxalinophenazine (III; R = Ph, R′ = R″ = Me): the calculated value is **402**. Compounds of type (IV) do not yield glyoxalinophenazines on treatment with a ketone in the presence of acid. The formation of a tribromo-derivative of compound (I; R = Ph) was used as evidence for the presence of the =NH group in anilino*apo*safranine since the isomer (IV; R = Ph) yielded only a dibromo-derivative.[1] We have now shown that the glyoxalinophenazine (III) yields a dibromo-derivative, the bromine atoms occupying the 1 : 4-positions of the phenazine nucleus. Further evidence for the absence of the =NH group in the glyoxalinophenazines is the stability of these compounds in boiling acetic anhydride.[1] In the degradation of anilino*apo*safranine (I; R = Ph) anilino*apo*safranone was isolated; the same product was obtained when the glyoxalinophenazine (III; R = Ph, R′ = R″ = Me) was degraded, the alkyl substituent being eliminated. It is therefore clear that only the nitrogen atoms at the 2- and the 3-position of the phenazine nucleus can be involved in the condensation. The presence of a glyoxaline ring in the compounds (III) is supported by the formation of ring compounds by the condensation of acetone with anthranilamide derivatives in the presence of hydrochloric acid.[3] Hydrogenation, in alcohol, at room temperature and pressure with Adams catalyst, resulted in the uptake by the glyoxalinophenazines of two molar equivalents of hydrogen to give colourless or nearly colourless solutions. On exposure to the air the solutions rapidly became dark-red and compounds of structure (V) separated. It is presumed that the quinonoid system in the compounds (III) is first reduced and then hydrogenolysis of the 2′ : 3′-bond of the glyoxaline ring occurs. This recalls the hydrogenolysis of quaternary salts of Schiff's bases recorded by Forbes.[4] The compounds (V) are unstable in boiling acetic anhydride. They give tribromo- in contrast to the dibromo-derivatives obtained from the glyoxalinophenazines. The compounds (V) do not fluoresce in solution and the close resemblance of their properties to those of anilino*apo*safranine derivatives (I) strongly supports the structure assigned.

The compounds (III; R = Ph, R′ = R″ = Me) and (V; R = Ph, R‴ = Pr^{i}) were examined spectrophotometrically in the infrared region by Mr. E. R. Stuart of the Chemical Laboratory. The samples were submitted under code numbers, B.621 and B.670 respectively. He reports as follows: "B.670 shows sharp absorption in the region of 3300 cm.$^{-1}$ characteristic of the =NH group.[5] This absorption is not shown by B.621. In addition an extra band at 2880 cm.$^{-1}$ in B.670 appears to indicate a tertiary carbon–hydrogen bond in this compound. This band is also absent from the spectrum of B.621.

"In both cases, the spectrum in the 1400—1600 cm.$^{-1}$ region is complex owing to phenyl residues and C=N bonds, but the spectra show considerable similarities. In B.670 a well-defined doublet at 1160—1120 cm.$^{-1}$ is taken as being indicative of an *iso*propyl group absent in B.621."

In the ultraviolet region these compounds have light absorption maxima at 280 and 475 mμ (B.670) and 270 and 465 mμ (B.621). For the hydrochlorides the maxima were observed at 280 and 490 mμ (B.670, HCl) and 270, 475, and 500 mμ (B.621,2HCl).

The use of *cyclo*alkyl ketones in the glyoxalinophenazine synthesis results in the formation of *spiro*-compounds of type (VI) which also undergo hydrogenolysis, giving *N*^{2}-*cyclo*alkylanilino*apo*safranine derivatives (V; R‴ = *cyclo*hexyl). The hydrogenation appears to be somewhat temperamental, as we have found that ring opening did not take place under experimental conditions apparently identical with those which we had already shown to be satisfactory for the hydrogenolysis. However, frequent repetition of the hydrogenation under varied conditions always has failed to open the glyoxaline ring in compounds (III) where R′ or R″ = aryl or where R = *cyclo*hexyl or benzyl. Hydrogenation of compound (III; R = Ph; R′ = Me, R″ = CH_2Cl) resulted in the loss of the chlorine atom, the product being the hydrochloride of the imine (V; R = Ph, R‴ = Pr^{i}). Again hydrogenation of the glyoxalino-compound (III; R = Ph, R = Me,

[3] Carrington, *J.*, 1955, 2527.
[4] Forbes, *J.*, 1955, 3926.
[5] Colthup, *J. Opt. Soc. Amer.*, 1950, **40**, 397.

R″ = CH_2·CO_2Et) resulted in considerable decomposition and no identifiable material was isolated; however, this compound was readily reduced in ether by lithium aluminium hydride to the corresponding alcohol (III; R = Ph, R′ = Me, R″ = CH_2·CH_2·OH), and the latter was then hydrogenated to yield the ring-opened compound (V; R = Ph, R′ = Me, R″ = CH_2·CH_2·OH).

When tested in experimental tuberculosis in mice, some of the compounds of type (V) have shown greater protective activity than we have encountered so far with any other type of compound. The biological details will be published elsewhere.

Experimental

Glyoxalinophenazines (III) *from* (a) o-*Phenylenediamines and* (b) *Anilinoaposafranines.*—The following are typical preparations:

5 : 1′-*Di*-(p-*chlorophenyl*)cyclo*hexane*spiro-2′-*glyoxalino*(5′ : 4′-2 : 3)*phenazine* (VI; R = *p*-C_6H_4Cl). Method (a): 2-Amino-4′-chlorodiphenylamine hydrochloride (2·2 g.) and *cyclo*hexanone (2 c.c.) in ethanol (60 c.c.) were treated with *p*-benzoquinone (2 g.) in aqueous ethanol (2 : 1; 70 c.c.) at 30°. After 30 min. the solution was made alkaline with aqueous sodium hydroxide (10%), and the precipitate collected, dried, and chromatographed in benzene on alumina. The first material eluted exhibited a strong green-yellow fluorescence in solution and was obtained as orange crystals (1·3 g.), m. p. 299—301° (from benzene–ligroin) (Found: C, 70·9; H, 5·0; N, 10·5; Cl, 13·4. $C_{30}H_{24}N_4Cl_2$ requires C, 70·5; H, 4·7; N, 11·0; Cl, 13·9%).

In general the yields were about 50%, except in the case of *N-cyclo*hexyl-*o*-phenylenediamine where it was 10%. The compounds are stable in boiling acetic anhydride.

5 : 2′-*Dihydro*-2′ : 2′-*dimethyl*-5 : 1′-*diphenylglyoxalino*(5′ : 4′-2 : 3)*phenazine* (III; R = Ph, R′ = R″ = Me). Method (b): Anilino*apo*safranine (2 g.), acetone (50 c.c.), ethanol (40 c.c.), and polyphosphoric acid (7 g.) were heated under reflux for 5 hr. The mixture was made alkaline and the product purified as in the previous preparation. The *compound* was obtained as orange crystals (1·0 g.), m. p. 230—232° (from benzene–ligroin), identical with the product obtained from 2-aminodiphenylamine hydrochloride and acetone by method (a).

The other *compounds* in this series have been tabulated (Table 1).

Table 1. 2′ : 2′-*Substituted* 5 : 2′-*dihydro*-5 : 1′-*diphenylglyoxalino*-(5′ : 4′-2 : 3)*phenazines.*

(III; R = Ph)			Found (%)				Required (%)		
R′	R″	M. p.	C	H	N	Formula	C	H	N
Me	Me [a]	230—232°	81·3	6·2	12·7	$C_{27}H_{22}N_4,\frac{1}{2}C_6H_6$	81·8	5·6	12·7
Me	Et	173—176	80·5	6·0	13·1	$C_{28}H_{24}N_4$	80·8	5·8	13·5
Et	Et [b]	216—218	80·0	6·3	13·0	$C_{29}H_{26}N_4$	80·9	6·0	13·0
Me	Bu [a]	182—183	80·5	6·4	12·5	$C_{30}H_{28}N_4$	81·1	6·3	12·6
Me	CH_2·CO_2Et	151—152	75·7	6·0	11·5	$C_{30}H_{26}O_2N_4$	76·0	5·5	11·8
Me	CH_2·CH_2·OH	197—200	77·2	5·7	12·4	$C_{28}H_{24}ON_4$	77·8	5·6	13·0
Me	CH_2Cl [c]	187—190	73·8	5·5	12·4	$C_{27}H_{21}N_4Cl$	74·2	4·8	12·8
Me	Ph	223—225	83·7	5·5	10·7	$C_{32}H_{26}N_4,\frac{1}{2}C_6H_6$	83·5	5·4	11·1
Me	4-Pyridyl	265—266	80·3	5·1	14·7	$C_{31}H_{22}N_6$	80·0	5·0	15·1

5 : 1′-*Substituted* 5 : 2′-*dihydro*-2′ : 2′-*dimethylglyoxalino*(5′ : 4′-2 : 3)*phenazines.*

(III; R′ = R″ = Me) R								
p-C_6H_4Cl [d]	246—247	68·8	4·5	11·4	$C_{27}H_{20}N_4Cl_2$	68·8	4·3	11·9
p-C_6H_4Me	211—213	80·1	6·2	13·0	$C_{28}H_{26}N_4$	80·9	6·0	13·0
*cyclo*Hexyl	257—258	78·6	8·2	13·5	$C_{27}H_{34}N_4$	78·3	8·2	13·5
CH_2Ph	224—225	80·5	6·3	13·0	$C_{28}H_{26}N_4$	80·9	6·0	13·0

5 : 1′-*Substituted* 5 : 2′-*dihydro*cyclo*hexane*spiro-2′-*glyoxalino*(5′ : 4′-2 : 3)-*phenazines.*

(VI) R =								
Ph	292—294	81·7	6·5	12·1	$C_{30}H_{28}N_4$	81·4	5·9	12·7
p-C_6H_4Cl [e]	299 [f]	70·9	5·0	10·5	$C_{30}H_{24}N_4Cl_2$	70·5	4·7	11·0
p-C_6H_4·OPr^i	289	76·9	6·8	9·4	$C_{33}H_{34}O_2N_4$	77·4	6·8	10·0

All compounds recrystallised from benzene–ligroin. [a] *M* (Rast), 420. $C_{27}H_{22}N_4$ requires *M*, 402. *Hydrochloride*, red crystals, m. p. 245° (decomp.) (Found: N, 11·5; Cl, 14·4. $C_{27}H_{22}N_4,2HCl$ requires N, 11·8; Cl, 15·0%); *methosulphate*, red-brown, m. p. 265° (decomp.) [Found: N, 8·5; S, 9·5. $C_{27}H_{22}N_4,2(CH_3)_2SO_4$ requires N, 8·6; S, 9·8%]. [b] Also m. p. 145—147°. [c] Found: Cl, 8·1. $C_{27}H_{21}N_4Cl$ requires Cl, 8·1%. [d] Found: Cl, 14·8. $C_{27}H_{20}N_4Cl_2$ requires Cl, 15·1%. [e] Found: Cl, 13·3. $C_{30}H_{24}N_4Cl_2$ requires Cl, 13·9%. [f] With decomp.

2-N-iso*Propylanilino*apo*safranine* (3 : 5-*Dihydro*-3-*imino*-5-*phenyl*-2-N-iso*propylanilino*-*phenazine*).—The following is a typical hydrogenation: 5 : 2′-Dihydro-2′ : 2′-dimethyl-5 : 1′-diphenylglyoxalino(5′ : 4′-2 : 3)phenazine (1·5 g.), ethanol (80 c.c.), and Adams catalyst (0·1 g.) were shaken in an atmosphere of hydrogen at room temperature and pressure until an almost colourless solution was obtained; two mols. were consumed. The solution was filtered and became deep red on exposure to the air, and dark red crystals (1·2 g.) separated, having m. p. 198—199° (Found: C, 79·9; H, 6·0; N, 13·7. $C_{27}H_{24}N_4$ requires C, 80·2; H, 5·9; N, 13·9%).

The other *compounds* in this series have been tabulated (Table 2).

TABLE 2. N²-*Substituted anilino*apo*safranine derivatives.*

(V; R = Ph; R‴ = CHR′R″)			Found (%)				Required (%)		
R′	R″	M. p.	C	H	N	Formula	C	H	N
Me	Me [a]	198—199°	79·9	6·0	13·7	$C_{27}H_{24}N_4$	80·2	5·9	13·9
Me	Et	174	80·1	6·2	13·5	$C_{28}H_{26}N_4$	80·4	6·2	13·4
Me	CH_2·CH_2·OH	212—214	77·2	6·1	12·9	$C_{28}H_{26}ON_4$	77·4	6·0	12·9
Et	Et	167—168	80·3	6·6	13·1	$C_{29}H_{28}N_4$	80·6	6·5	13·0
Me	Bu[a]	164	80·8	6·9	12·5	$C_{30}H_{30}N_4$	80·7	6·7	12·6
(V; R‴ = Pr[i]) R									
p-C_6H_4Cl [b]	.....	211—213	68·3	4·7	11·5	$C_{27}H_{22}N_4Cl_2$	68·5	4·7	11·8
p-C_6H_4Me		202—204	80·2	6·5	13·1	$C_{29}H_{28}N_4$	80·6	6·5	13·0
(V; R‴ = *cyclo*hexyl) R									
Ph		160—162	81·0	6·7	12·5	$C_{32}H_{32}N_4$	81·1	6·3	12·6
p-C_6H_4Cl [c]		248—250	70·1	5·0	11·0	$C_{32}H_{28}N_4Cl_2$	70·2	5·1	10·9
p-C_6H_4·OPr[i]	.....	200	77·7	7·1	—	$C_{34}H_{40}O_2N_4$	77·1	7·1	—

All the compounds in this Table were recrystallised from ethanol. [a] *Hydrochloride*, green crystals, m. p. 250° (decomp.) (Found: N, 12·7; Cl, 7·8. $C_{27}H_{24}N_4$,HCl requires N, 12·7; Cl, 8·1%); *methosulphate*, green crystals, m. p. 218° (decomp.) [Found: N, 10·4; S, 5·2. $C_{27}H_{24}N_4$,$(CH_3)_2SO_4$ requires N, 10·6; S, 6·0%]. [b] Found: Cl, 15·2. $C_{27}H_{22}N_4Cl_2$ requires Cl, 15·0%. [c] Found: Cl 13·9. $C_{32}H_{28}N_4Cl_2$ requires Cl, 13·8%.

Bromination of 5 : 2′-*Dihydro*-2′ : 2′-*dimethyl*-5 : 1′-*diphenylglyoxalino*(5′ : 4′-2 : 3)*phenazine*.—The base in carbon tetrachloride was stirred with excess of bromine in the same solvent. The precipitated hydrobromide was converted into the 1 : 4-*dibromo-base* with alcoholic sodium hydroxide and recrystallised from benzene–light petroleum. It was an orange powder, m. p. 245° (decomp.) (Found: Br, 24·8. $C_{27}H_{20}N_4Br_2,C_6H_6$ requires Br, 25·1%). Identical material was obtained when the glyoxalinophenazine was heated under reflux in chloroform with *N*-bromosuccinimide, and the product recrystallised from benzene–light petroleum.

Bromination of N²-iso*Propylanilino*apo*safranine*.—By using the methods described the 1 : 4 : N²-*tribromo-base* was obtained as a dark brown powder, m. p. 310° (Found: Br, 36·6. $C_{27}H_{21}N_4Br_3$ requires Br, 37·4%).

5 : 2′-*Dihydro*-5 : 1′-*diphenyl*-2′-(2-*hydroxyethyl*)-2′-*methylglyoxalino*(5′ : 4′-2 : 3)*phenazine*.—2′-Ethoxycarbonylmethyl-5 : 2′-dihydro-5 : 1′-diphenyl-2′-methylglyoxalino(5′ : 4′-2 : 3)phenazine (1·1 g.) in dry ether (250 c.c.) was added to a suspension of lithium aluminium hydride (1·5 g.) in dry ether (100 c.c.). After 3 hr. water was added and then dilute sulphuric acid. The acid layer was separated and made alkaline with aqueous sodium hydroxide. The precipitate was dried and extracted with benzene, and the extract chromatographed on alumina. The *glyoxalinophenazine* was obtained as a yellow powder (0·2 g.), m. p. 197—200° (Found: C, 77·3; H, 5·7; N, 12·4. $C_{28}H_{24}ON_4$ requires C, 77·8; H, 5·6; N, 13·0%).

Grateful acknowledgment is made to Mr. E. R. Stuart, University Chemical Laboratory, for the infrared spectrophotometric data, and to J. R. Geigy S.A., Basle, Switzerland, for financial aid.

LABORATORIES OF THE MEDICAL RESEARCH COUNCIL OF IRELAND,
TRINITY COLLEGE, DUBLIN.

[*Received, April 20th*, 1956.]

651. *Co-ordination Complexes of Methyl Derivatives of Indium and Thallium.*

By G. E. Coates and R. A. Whitcombe.

Trimethylindium forms 1 : 1 co-ordination complexes with ammonia, trimethylamine, and some methyl derivatives of Group VB and VIB elements. The heat of co-ordination to trimethylamine and to trimethylphosphine is a little less than that of trimethylgallium. The co-ordination of trimethylthallium was studied qualitatively and the greatest co-ordination affinity appears to be shown to trimethylamine, trimethylphosphine, and dimethyl sulphide and selenide. Trimethylthallium is a weaker acceptor than trimethylindium, hence the order of acceptor character to trimethylamine among the Group III and IIIB trimethyls is B < Al > Ga > In > Tl. Some dimethylamino-, methoxy-, methylthio-, and methylseleno-derivatives of the dimethylindium and dimethylthallium radicals have been prepared; the greater thermal stability, lower sensitivity to hydrolysis, and absence of reaction with trimethylamine of the S and the Se compounds suggest that thallium and possibly indium might form dative π bonds to S and Se.

Since various co-ordination complexes are formed by trimethylaluminium [1] and trimethylgallium,[2] the reported inability of trimethylindium [3] to form complexes, even with ammonia, appeared worthy of further investigation. Another reason for examining the co-ordination of derivatives of indium(III) and thallium(III) was to obtain evidence about the possibility of the occurrence of dative π bonding to donors such as sulphur or phosphorus. Much evidence from the chemistry of the Group IIIB and the Group VIII elements suggests that such bonds are more likely to be formed by the heavier than by the lighter members of a group. Since the inorganic compounds of thallium(III) are reduced by the donor substances of interest in this connection, it is necessary to use an organic derivative such as trimethylthallium.

Trimethylindium forms the complexes listed in the Table.

Complex	M. p.	B. p. (extrap.)	*A* *	*B* *	L_v †	Temp. range
Me_3In,NMe_3(s)	66·2—66·4°	—	2590	8·802	11·9 ‡	30—65°
Me_3In,NMe_3(l)	—	171°	2460	8·402	11·3	70—100
Me_3In,PMe_3	46·5	189	2832	9·015	13·0	50—110
$Me_3In,AsMe_3$	28·2—28·8	155	2590	8·925	11·9	30—95
Me_3In,OEt_2	—	147	2175	8·066	10·0	20—60
Me_3In,SMe_2	19·0—19·5	185	1808	6·825	8·3	30—85
Me_3In,NH_3	28·5—29·0	—	—	—	—	—
$(Me_2In{\cdot}NMe_2)_2$	—	—	1890	5·61	8·6	30—75
	—	—	3018	8·861	13·8	75—140

* $\log_{10}$ (v. p.)$_{mm.}$ = $-(A/T) + B$.
† Latent heat of evaporation (kcal./mole).
‡ Latent heat of sublimation.

Heats of dissociation in the gas phase were measured by the vapour-density method used in previous studies; [2] that of the trimethylamine complex is 19·9 ± 0·5 kcal./mole, and that of the trimethylphosphine complex 17·1 ± 0·8 kcal./mole. The other complexes (trimethylarsine, dimethyl ether, and dimethyl sulphide) were so extensively dissociated that no useful equilibrium measurements could be made. The ammine, Me_3In,NH_3, evolved methane very slowly even at room temperature; at 70—80° methane evolution was rapid and amounted to one mole per g.-atom of indium. The resulting amide, $(Me_2In{\cdot}NH_2)_x$, melted at 120—124° to a thick syrup which underwent further decomposition; it was not appreciably volatile, unlike its gallium analogue,[2a] $(Me_2Ga{\cdot}NH_2)_2$.

Trimethylindium forms a 1 : 1 co-ordination compound with dimethylamine, $Me_3In,NHMe_2$, liquid at room temperature, which also evolves a mol. of methane when heated to 140—160°. The product is sufficiently stable and volatile to allow its vapour

[1] H. C. Brown and Davidson, *J. Amer. Chem. Soc.*, 1942, **64**, 316.
[2] (*a*) Coates, *J.*, 1951, 2003; (*b*) Coates and Hayter, *J.*, 1953, 2519.
[3] Dennis, Work, and Rochow, *J. Amer. Chem. Soc.*, 1934, **56**, 1047.

density to be measured in the temperature range 130—180°, and it is dimeric like the gallium compound [2a] $(Me_2Ga{\cdot}NMe_2)_2$. Again like the gallium analogue, it is dimorphic and has the curious property that the low-temperature form (below 70°) appears to have a *lower* latent heat of sublimation ($\Delta H_s \simeq 9$ kcal./mole) than the high-temperature form (above 80°, $\Delta H_s = 13{\cdot}8$ kcal./mole). The difference in latent heat is similar to that observed for the gallium compound ($\Delta H_s = 6{\cdot}6$ kcal./mole below 55° and 12·5 kcal. above 80°). Crystals of $Me_2In{\cdot}NMe_2$ formed by condensation from the vapour at or near room temperature are well formed and have sharply defined faces and angles, but those condensing above about 80° are of quite different appearance and have a strong tendency to form rounded edges. Crystals of the second type may persist below 50—80° for several minutes, but suddenly change from a transparent to an opaque polycrystalline mass if slight local cooling is applied.

FIG. 1.

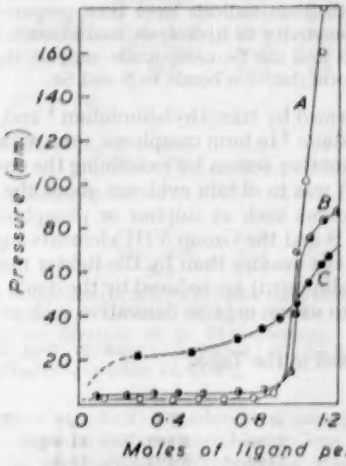
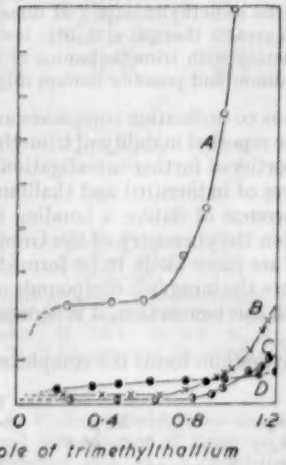


FIG. 2.



Moles of ligand per mole of trimethylthallium

FIG. 1. *A, Trimethylamine* (○). *B, Trimethylphosphine* (◑). *C, Trimethylarsine* (●).

FIG. 2. *A, Dimethyl ether* (○). *B, Dimethyl sulphide* (×). *C, Dimethyl selenide* (◑). *D, Dimethyl telluride* (●).

Dimethylindium methoxide results from the reaction, vigorous at −98° (m. p. of methanol), between trimethylindium and methanol. It is a colourless viscous liquid, whose molecular weight (ebullioscopically in benzene) varies with concentration but indicates a degree of association of about three. Though very sensitive to hydrolysis, it is stable to dry air. The initial product from trimethylaluminium [1] and methanol is a mixture of liquid and solid, but this becomes a homogeneous crystalline substance when heated at 90°; no crystalline material could be obtained from the indium product by similar treatment. In contrast, the methylthio-derivative, obtained from trimethylindium and methanethiol in ether solution, is a colourless crystalline solid which can be sublimed in a vacuum and is dimeric in benzene solution. It is far less sensitive to hydrolysis than the methoxide, but is decomposed rapidly by dilute acids. Neither compound reacts with trimethylamine.

The reported ease with which trimethylthallium can be separated from ether by vacuum-distillation [4] indicates a low co-ordination affinity. Since trimethylthallium explodes with violence when heated to about 100°, no attempts were made to study gas dissociation equilibria. Instead some qualitative information was obtained by measuring the vapour pressure of various ligands in equilibrium with trimethylthallium at 0° (Figs. 1 and 2). The vapour pressure of trimethylthallium is 2 mm. at 0° C.

[4] Gilman and R. G. Jones, *J. Amer. Chem. Soc.*, 1946, **68**, 517.

Trimethylamine, trimethylphosphine, dimethyl sulphide, and dimethyl selenide all appear to form 1 : 1 complexes with trimethylthallium. Dimethyl ether, dimethyl telluride, and trimethylarsine are all evidently very weak donors and in the case of dimethyl telluride there is scarcely evidence for any reaction (v. p. of pure dimethyl telluride is 15 mm. at 0°). Only the trimethylphosphine and the dimethyl sulphide complexes had nearly sharp melting points (27—28° and −0·5° respectively), the others melting over a range usually a little below 0°. It should be noted that for all complexes studied between any given Group III trimethyl and the various Group VB trimethyls the melting point of the complex increases with its stability. The data of Fig. 1 merely indicate that trimethylamine and trimethylphosphine are donors of comparable strength, both being much stronger than trimethylarsine, but the significantly higher melting point of the phosphine complex is some slight evidence for an order $Me_3P > Me_3N \geqslant Me_3As$. Such an order, or even if the amine and the phosphine were equivalent, would be evidence for the strengthening of the co-ordinate bond in the phosphine complex by a dative π bond. In the absence of such double bonding trimethylamine always appears to co-ordinate more strongly than trimethylphosphine.

Since information is now available about the co-ordination complexes of all the trimethyl derivatives of the Group III and IIIB elements, it is apparent that the order of acceptor character to a constant donor such as trimethylamine is $B < Al > Ga > In > Tl$. The heats of co-ordination to trimethylamine are: Me_3B [5] 17·6, Me_3Al [1,6] > 21, Me_3Ga [6] 21·0, Me_3In 19·9 kcal./mole, Me_3Tl unknown, but there is appreciable dissociation at 0°.

Certain thallium compounds were prepared, in which the dimethylthallium group is bound to a donor atom, for purposes of comparison with aluminium, gallium, and indium analogues. Dimethylthallium methoxide [7] and ethoxide [8] have already been described and are reactive and very easily hydrolysed. A specimen of the methoxide was prepared in the course of this investigation and was found not to react with trimethylamine in common with all the other dimethylmetal methoxides of Group III.

An attempt at the preparation of dimethyl-thallium dimethylamide, $Me_2Tl{\cdot}NMe_2$, by thermal decomposition of the dimethylamine adduct of trimethylthallium failed because general decomposition with deposition of thallium took place simultaneously with evolution of methane. The compound was, however, prepared from dimethylthallium bromide and dimethylaminolithium, and can be purified quite easily by sublimation. It is dimeric in benzene, very sensitive to hydrolysis, and, like the methoxide, decomposes at 120—130°. It does not absorb trimethylamine.

The sulphur and selenium derivatives $(Me_2Tl{\cdot}SMe)_2$ and $(Me_2Tl{\cdot}SeMe)_2$, obtained from dimethylthallium fluoride and sodium methyl sulphide (or selenide) in methanol, are, in contrast, much more stable thermally and are relatively insensitive to hydrolysis. Like the indium compound $(Me_2In{\cdot}SMe)_2$ neither absorbed trimethylamine; this contrasts with the reaction of $(Me_2Al{\cdot}SMe)_2$,[1] $(Me_2Ga{\cdot}SMe)_2$, and $(Me_2Ga{\cdot}SeMe)_2$ [2b] with trimethylamine. The sulphur and selenium compounds appear to be generally rather more stable than the corresponding oxygen compounds, and this might well be due to some strengthening of the bonds between thallium (or even indium) and sulphur or selenium by the formation of a dative π bond.

Experimental

Most of the compounds described were prepared and studied in a vacuum-apparatus. Trimethylindium,[3] trimethylthallium,[4] and the various donor substances [2a] were prepared as previously described. All experiments with trimethylthallium took place in a darkened room, and care was taken to reduce exposure of the substance to mercury with which it slowly reacts with formation of thallium amalgam and dimethylmercury.

Trimethylindium–Ammonia.—Trimethylindium (0·5813 g., *i.e.*, 81·4 N-c.c.) and ammonia (81·4 N-c.c.) were condensed in the "high-temperature bulb." [2a] Reaction occurred as the

[5] H. C. Brown and Gerstein, *J. Amer. Chem. Soc.*, 1950, **72**, 2923.
[6] Coates and Huck, *J.*, 1952, 4511.
[7] Menzies and Walker, *J.*, 1934, 1131.
[8] Menzies, *J.*, 1930, 1571.

ammonia melted, giving colourless acicular crystals of the *adduct*, m.p. 28·5—29·5°. Methane, identified by its vapour pressure at −196°, was slowly evolved at room temperature at the rate of about 1 c.c. a day. When the adduct was heated to 70—80° methane was rapidly evolved and the total quantity collected (by Töpler pump) was 81·35 N-c.c. (1 mol. = 81·4 N-c.c.). The white residue, which was involatile at room temperature, was therefore *aminodimethylindium*, $Me_2In{\cdot}NH_2$, and melted with decomposition at 120—124° to a thick syrup.

Dimethylindium Methoxide.—Anhydrous methanol (27·4 N-c.c.) was condensed on trimethylindium (0·1958 g., 27·4 N-c.c.) at −183°. Reaction was apparent as soon as the methanol melted, and was completed by gentle warming. Methane (27·3 N-c.c.) was collected. The *product* is a colourless rather viscous liquid, very easily hydrolysed by moist air. It could not be made to crystallise as it always formed a clear glass. A larger quantity was prepared for molecular-weight measurement (Found: *M*, ebullioscopically in benzene: 1·4% solution, 623; 2·5%, 586; 4·0%, 548. $C_3H_{27}O_3In_3$ requires *M*, 528).

Tetramethyl-μμ′-bismethylthiodi-indium.—Trimethylindium (2·972 g., 18·58 mmoles), methanethiol (416·1 N-c.c., 18·58 mmoles), and dry ether (5 c.c.) were condensed in an ampoule connected to a ½-l. bulb. Methane was rapidly evolved when the ampoule was allowed to warm. The mixture was cooled in liquid nitrogen, and the methane pumped away. The remaining volatile matter (mainly ether) was then removed, and the colourless solid residue was sublimed in a vacuum; it then had m. p. 122—124° (decomp.) (Found: C, 18·6; H, 4·6; In, 60·3%; *M*, ebullioscopic in benzene, 370, 354, 346. $C_6H_{18}S_2In_2$ requires C, 18·75; H, 4·7; In, 59·9%; *M*, 384). The compound is freely soluble in benzene.

Tetramethyl-μμ′-bisdimethylaminodi-indium.—Trimethylindium (0·0723 g., 10·1 N-c.c.) and dimethylamine (10·1 N-c.c.) were condensed in the high-temperature bulb and formed a liquid adduct. The bulb was heated at 160° until no further pressure change was noted (½ hr.), and methane (10·1 N-c.c.) was subsequently collected by Töpler pump from the cooled bulb. The product was then heated until it had all become gaseous and the volume (5·1—5·2 N-c.c. from 140° to 160°) indicated the dimeric constitution.

Dimethylindium–acetylacetone, from trimethylindium and acetylacetone, sublimed in a vacuum, and decomposed at 118° (Found: C, 34·75; H, 5·8; In, 56·9. $C_7H_{13}O_2In$ requires C, 34·4; H, 5·3; In, 56·6%).

Tetramethyl-μμ′-bisdimethylaminodithallium.—Dimethylthallium bromide (31·4 g., 0·1 mole) was added with continuous stirring to a solution of lithium dimethylamide obtained from phenyllithium (120 c.c. of 0·84M-solution in ether) and a slight excess of dimethylamine (30 c.c. of 4·1M-solution in ethylene glycol dimethyl ether). The greater part of the solid dissolved during ½ hr. at room temperature. The solvent was evaporated and the *product* (19·5 g., 70%) separated by high-vacuum sublimation, which was rapid at 110°. The substance was exceedingly sensitive to moisture and was analysed by alkaline hydrolysis (Found: NMe_2, 15·6; Me_2Tl, as Me_2TlI, 84·3%; *M*, ebullioscopic in benzene, 541, 560, 545. $C_8H_{24}N_2Tl_2$ requires NMe_2, 15·8; Me_2Tl, 84·2%; *M*, 557).

Tetramethyl-μμ′-bismethylthiodithallium, was obtained from the sodium salt of methanethiol and dimethylthallium fluoride in methanol as a very pale yellow precipitate and was separated from sodium fluoride by crystallisation from benzene, or, in some instances, by vacuum-sublimation. It forms colourless crystals, m. p. 207—208° (decomp. with darkening at 190°) (Found: C, 12·86; H, 3·4; Tl, 72·25%; *M*, ebullioscopic in benzene, 544, 609, 600. $C_4H_{12}S_2Tl_2$ requires C, 12·81; H, 3·2; Tl, 72·6%; *M*, 563).

Tetramethyl-μμ′-bismethylselenodithallium, similarly prepared from dimethylthallium fluoride and sodium methyl selenide (from methaneselenol [9] and sodium methoxide) in methanol, was purified by vacuum-sublimation and formed colourless crystals, m. p. 210° (decomp. with darkening at ~170°) (Found: C, 11·3; H, 2·9; Tl, 61·9%; *M*, ebullioscopic in benzene, 684, 671, 689. $C_4H_{12}Se_2Tl_2$ requires C, 11·0; H, 2·7; Tl, 62·2%; *M*, 657).

One of us (R. A. W.) thanks the Imperial Smelting Corporation for the award of a research fellowship. The authors are grateful to Dr. J. Chatt for helpful comment.

THE UNIVERSITY, BRISTOL.
THE UNIVERSITY, DURHAM.

[*Received, April 20th*, 1956.]

[9] Coates, *J.*, 1953, 2839.

652. *The Heat of Hydrolysis of Ethyl Orthosilicate and of Chlorotriethoxysilane.*

By T. Flitcroft and H. A. Skinner.

The heat of hydrolysis at 25° c of ethyl orthosilicate in N-hydrochloric acid solution, and also in acetone–N-hydrochloric acid, has been measured. The heat of hydrolysis of chlorotriethoxysilane in water has been measured. From the heats of hydrolysis, the heats of formation have been derived :

ΔH_f° [$Si(OEt)_4$, liq.] = −330·2 kcal./mole, and
ΔH_f° [$Si(OEt)_3Cl$, liq.] = −291·0 kcal./mole.

These are based on the value $\Delta_f^\circ(SiO_2,2H_2O)$ = −346·2 kcal./mole.

The heat of the gaseous redistribution reaction between ethyl orthosilicate and silicon tetrachloride to form chlorotriethoxysilane is calculated, ΔH_r = −4·3 kcal./mole of $Si(OEt)_3Cl$.

Ogier [1] measured the heat of hydrolysis of ethyl orthosilicate in pure water, obtaining the value $-\Delta H_{hyd.}$ = 21·6 kcal./mole. He stated that the hydrolysis occurred rapidly, which would now suggest that his sample was impure. Thompson [2] has found that the pure substance hydrolyses very slowly in water, but much more rapidly in acid solutions. He reported a " preliminary " value of *ca.* 18 kcal./mole for $-\Delta H_{hyd.}$ in 0·1N-hydrochloric acid. We have found that the hydrolysis is very slow in pure water, reasonably rapid in N-hydrochloric acid, and fast in N-hydrochloric acid–acetone. The heat of hydrolysis of chlorotriethoxysilane has not previously been reported.

Both compounds are hydrolysed with the precipitation of silica; we have not investigated the precise nature of the precipitates. However, several authors have reported on the solid precipitates obtained on hydrolysis of ethyl orthosilicate, which appear to be hydrated silicas, SiO_2,xH_2O. Theissen and Koerner [3] isolated a number of distinct species, including $SiO_2,2H_2O$, $2SiO_2,3H_2O$, and SiO_2,H_2O. The heats of decomposition of these into amorphous silica and water were found to be in the range 1·2—1·5 kcal./mole of SiO_2. The value given in " Selected Values of Chemical Thermodynamic Properties " [4] for the heat of formation of the dihydrate is derived from the heat of decomposition (1·5 kcal./mole) of the dihydrate,[3] and a chosen value ΔH_f° (SiO_2, amorphous) = −202·5 kcal./mole. The latter, however, seems unsatisfactory in view of the recent finding by Humphrey and King [5] for the heat of combustion of pure silicon leading to ΔH_f° (SiO_2, amorphous) = 208·1 kcal./mole ± 0·3 kcal./mole. Accordingly, we have adopted the value ΔH_f° ($SiO_2,2H_2O$) = −346·2 kcal./mole in this work.

Experimental

Preparation of Compounds.—A sample of ethyl orthosilicate supplied by the Monsanto Chemical Company was distilled through an 18" Fenske column, and the main fraction (b. p. 166·1° ± 0·1°/765 mm.) collected. This was redistilled through an 8" gauze-packed column, and the fraction (b. p. 58·1° ± 0·2°/7 mm.) retained. Chlorotriethoxysilane was prepared according to the method of Schumb and Stevens,[6] by the controlled reaction between ethanol and silicon tetrachloride in ether. The product was purified by fractional distillation, and the main fraction redistilled through an 8" gauze-packed column (b. p. 157·2° ± 0·2°/765 mm.).

Calorimeter.—The calorimeter, which has been previously described,[7] was immersed in a thermostat maintained at 25° c. The hydrolyses were carried out by breaking glass ampoules containing weighed amounts of reactant under the surface of the solvent in the Dewar vessel,

[1] Ogier, *Ann. Chim. Phys.*, 1880, **20**, 5.
[2] Thompson, *J.*, 1953, 1908.
[3] Thiesson and Koerner, *Z. anorg. Chem.*, 1931, **197**, 307.
[4] Nat. Bureau Stands., Washington, Circular 500, 1952.
[5] Humphrey and King, *J. Amer. Chem. Soc.*, 1952, **74**, 2041.
[6] Schumb and Stevens, *ibid.*, 1947, **69**, 726.
[7] Skinner and Smith, *Trans. Faraday Soc.*, 1953, **49**, 601.

and following the ensuing temperature changes through the resistance changes of a shielded thermistor element immersed in the solution.

Units.—The calorimeter was calibrated electrically by the substitution method. Heat quantities are given in thermochemical calories, 1 cal. = 4·1840 abs. joules.

Results.—(1) *Ethyl orthosilicate.* The first series of experiments were carried out with 500 ml. of N-hydrochloric acid in the Dewar vessel. The hydrolyses required *ca.* 15 min. for completion, and the ethyl orthosilicate tended to float on the acid solution. A second series of experiments used a mixture of 320 ml. of acetone and 160 ml. of N-hydrochloric acid; in this, hydrolysis was rapid, and the orthosilicate did not float. Silica was precipitated in both sets of experiments, and we have presumed this to be the dihydrate, $SiO_2,2H_2O$.

The observed heats of hydrolysis, $\Delta H_{obs.}$, are listed in Table 1. The heats refer to the processes:

(1) $Si(OEt)_4$ (liq.) + nHCl(55H_2O) ⟶ $SiO_2,2H_2O$ (ppt.) + [4EtOH + nHCl] in [55n − 4]H_2O

and

(2) $Si(OEt)_4$ (liq.) + mHCl(55H_2O,22C_2H_6O) ⟶ $SiO_2,2H_2O$ (ppt.) + [4EtOH + mHCl + 22C_2H_6O] in [55m − 4]H_2O

The column headed $\Delta H_{hyd.}$ gives the heats (derived from $\Delta H_{obs.}$ on correction for the heat of solution of ethyl alcohol in the solvents used) of the idealized hydrolysis: $Si(OEt)_4$ (liq.) + $4H_2O$ (liq.) ⟶ $SiO_2,2H_2O$ (ppt.) + 4EtOH (liq.). The solution heat correction terms were measured separately, viz:

(*a*) solution of ethyl alcohol in N-hydrochloric acid, $\Delta H_{sols.} = -2{\cdot}15$ kcal./mole of ethyl alcohol

and (*b*) solution of ethyl alcohol in the acetone–N-hydrochloric acid, $\Delta H_{sols.} = 0{\cdot}28$ kcal./mole of ethyl alcohol.

TABLE 1. *Heat of hydrolysis of ethyl orthosilicate.*

(Expts. 1—7 were in N-hydrochloric acid; Expts. 8—10 in acetone–hydrochloric acid.)

Expt.	Wt. (g.)	n	$-\Delta H_{obs.}$ (kcal./mole)	$-\Delta H_{hyd.}$ (kcal./mole)	Expt.	Wt. (g.)	n	$-H_{obs.}$ (kcal./mole)	$-\Delta H_{hyd.}$ (kcal./mole)
1	1·2177	85	16·85	8·25	6	1·0045	104	17·09	8·49
2	1·1192	93	16·83	8·23	7	1·4538	72	16·98	8·38
3	1·1672	89	16·73	8·13	8	0·9570	35	6·96	8·08
4	2·0357	51	16·62	8·02	9	1·2871	26	7·11	8·23
5	1·1018	94	16·55	7·95	10	1·3070	26	6·89	8·01

Mean: 8·20 ± 0·2

TABLE 2. *Heat of hydrolysis of chlorotriethoxysilane.*

Expt.	Wt. (g.)	% purity (Cl analysis)	Total cals., obs.	cals. from $Si(OEt)_4$	$-\Delta H_{corr.}$ (kcal./mole)
1	1·2874	97·7	183·7	2·6	28·6
2	1·1127	95·7	155·3	4·2	28·2
3	1·0524	94·6	149·0	4·9	28·7
4	1·0418	94·8	156·1	4·7	28·4
5	0·9614	95·5	135·2	3·8	28·4
6 *	0·9862	82·1	132·6	15·4	28·7 *
7 *	1·3511	66·1	168·4	40·0	28·6 *

Mean: 28·5 ± 0·2

* Runs 6 and 7: ethyl orthosilicate was added to the sample. The corrections for the heat of hydrolysis of the orthosilicate impurity were based on $-\Delta H = 18{\cdot}2$ kcal./mole of ethyl orthosilicate. This value differs from that in Table 1, since the heat of solution of ethyl alcohol is larger in dilute (*ca.* 0·01N) than in N-hydrochloric acid.

(2) *Chlorotriethoxysilane.* Chlorotriethoxysilane hydrolyses easily in water, and all the experiments were made with 500 ml. of distilled water in the calorimeter. Aliquot samples from the final solutions were titrated for hydrochloric acid against N/40-sodium hydroxide, and for chloride ion by Volhard's method. The analyses showed that the chlorotriethoxysilane was contaminated slightly, since the chlorine content was found generally to be low (95—98%): Schumb and Stevens [6] similarly observed that the chlorine content of their preparation was a few units % low. The impurity is very likely to be ethyl orthosilicate, and microanalysis of

the sample for carbon and hydrogen supported this. The observed heats of hydrolysis were corrected on the assumption that the impurity was ethyl orthosilicate. In some experiments, the chlorotriethoxysilane was deliberately diluted with ethyl orthosilicate in order to check that the corrections were properly applied. The values given under $\Delta H_{corr.}$ in Table 2 relate to the reaction :

$$Si(OEt)_3Cl\ (liq.) + (n + 4)H_2O\ (liq.) \longrightarrow SiO_2,2H_2O\ (ppt.) + (3EtOH + HCl)\ in\ nH_2O\ (soln.)$$

Values of n varied from 3700 to 6000.

Discussion

From the mean values of $\Delta H_{hyd.}$ (Table 1) and $\Delta H_{corr.}$ (Table 2), together with certain known heats of formation, we may derive values for the heats of formation of liquid ethyl orthosilicate and of liquid chlorotriethoxysilane. Using the following data,[4] ΔH_f° (H_2O, liq.) = 68·32 kcal./mole, ΔH_f° (EtOH, liq.) = −66·36 kcal./mole, ΔH_f° (HCl, aq.) = −39·97 kcal./mole, ΔH_f° (EtOH, aq.) = −68·85 kcal./mole, and the value for ΔH_f° ($SiO_2,2H_2O$, ppt.) discussed earlier, we derive :

$$\Delta H_f^\circ\ [Si(OEt)_4, liq.] = -330{\cdot}2\ kcal./mole\ and\ \Delta H_f^\circ\ [Si(OEt)_3Cl, liq.] = -291{\cdot}0\ kcal./mole.$$

Although the calorimeter errors in the heats of hydrolysis are small, lying within limits of less than $\pm \frac{1}{2}$ kcal./mole, the absolute errors attached to the derived ΔH_f° values may be significantly larger. The main difficulty in assessing these arises from our assumption that the silica formed on hydrolysis is precipitated *in toto* as dihydrate. It is possible that part of the silica formed remained in colloidal solution. Roth and Schwartz,[8] and also Chernick,[9] observed from studies on the heat of hydrolysis of silicon tetrachloride in water at room temperature that silica was not precipitated under the conditions they used, but remained entirely in colloidal solution. In the present hydrolysis experiments, the amount of silica remaining in solution was not determined, although it was probably small as judged by the bulk of precipitated silica formed. Nevertheless, this weakness in the present study remains, and the overall error limits in the derived ΔH_f° values may amount to $\pm$ 2 kcal./mole in consequence.*

It was originally intended to measure the heats of hydrolysis of each compound belonging to the group $Si(OEt)_{4-n}Cl_n$ (n = 0—4) in order to examine the degree of constancy of the Si–Cl and Si–OEt bond energy term values within this group (*cf.* the similar studies by Skinner and Smith on the group of dimethylaminochloroborines [10] and ethoxychloroborines [11]). We have not completed this programme partly because of the difficulty of preparing the compounds in a satisfactory state of purity, and also because of the thermochemical uncertainties attendant upon partial precipitation of silica. The study by Chernick of the heat of hydrolysis of silicon tetrachloride confirmed the result obtained by Roth and Schwartz, and leads to the value ΔH_f° ($SiCl_4$,liq.) = −156·4 kcal./mole. Accepting the values $\Delta H_{vap.}$ = 7·0 kcal./mole [4] for the heat of vaporization of silicon tetrachloride, and $\Delta H_{vap.}$ = 10·0 kcal./mole [2] for the heat of vaporization of ethyl orthosilicate, and interpolating between these to derive $\Delta H_{vap.}$ ~9·2 kcal./mole for the heat of vaporization of chlorotriethoxysilane, we obtain −149·4, −320·2, and −281·8 kcal./mole, respectively, for the heats of formation of these compounds in their gaseous states. Hence, we may calculate the heat of the gaseous redistribution reaction : [12]

$$\tfrac{3}{4}Si(OEt)_4 + \tfrac{1}{4}SiCl_4 \longrightarrow Si(OEt)_3Cl$$

and obtain ΔH_r = −4·3 kcal./mole. It is admitted that the overall uncertainties in the heat of formation values are too large to allow much reliance to be put on this derived

* If as much as 50% of the total silica remained in solution in the experiments made with ethyl orthosilicate, a correction of 1·5 kcal./mole would be necessary, giving ΔH_f° = − 328·7 as opposed to −330·2 kcal./mole.

[8] Roth and Schwartz, *Z. phys. Chem.*, 1928, **134**, 456.
[9] Chernick, unpublished work.
[10] Skinner and Smith, *J.*, 1954, 2324.
[11] *Idem*, *ibid.*, p. 3920.
[12] Skinner, *Rec. Trav. chim.*, 1954, **73**, 991.

heat of redistribution; nevertheless, it is of interest that the redistribution heat is apparently of similar magnitude and sign to those measured by Skinner and Smith [11] in the group of chloroethoxyborines.

Tanake and Watase [13] recently reported on their measurements of the heat of combustion of liquid methyl orthosilicate, from which they derived the value ΔH_f° [$Si(OMe)_4$, liq.] = 300 kcal./mole. Thus, the increment in the heat of formation in passing from methyl to ethyl orthosilicate is *ca.* −30 kcal./mole, or −7·5 kcal./mole per CH_2 group. This is rather low by comparison with the CH_2 increments in passing from MeOH to EtOH, $B(OMe)_3$ to $B(OEt)_3$, $As(OMe)_3$ to $As(OEt)_3$, and $P(OMe)_3$ to $P(OEt)_3$, in which [14,15,16] the increments are *ca.* −9 kcal./mole per CH_2 group.

Chemistry Department, The University, Manchester. [*Received, April 26th*, 1956.]

[13] Tanake and Watase, *J. Chem. Phys.*, 1954, **22**, 1268.
[14] Charnley, Skinner, and Smith, *J.*, 1952, 2288.
[15] Charnley, Mortimer, and Skinner, *J.*, 1953, 1181.
[16] Chernick, Skinner, and Mortimer, *J.*, 1955, 3936.

---

653. *The Preparation and Properties of Some Plutonium Compounds. Part V.* Colloidal Quadrivalent Plutonium.*

By D. W. Ockenden and G. A. Welch.

Colloidal, or polymeric, quadrivalent plutonium has been separated from the ionic species of plutonium by ion exchange. The absorption spectrum of the colloid is distinctive, quite different from those of other species of plutonium, and varies slightly with the method of preparation. The rate of formation of the polymer in dilute nitric acid, its stability in more concentrated acid, its adsorption on certain surfaces, and other properties have been studied. The minimum and maximum molecular weights of the colloid have been calculated from diffusion experiments and from work with nuclear emulsion plates.

The existence of a colloidal, polymeric, form of quadrivalent plutonium has been known for many years. Most of the early work was done in America by Kraus, Werner, and others from 1944 to 1946 but, apart from general statements and a few diagrams,[1] few papers have been published. Thus it was known that the polymer, recognised by its bright green colour and diffuse absorption spectrum, was formed in quadrivalent plutonium solutions where the acidity was 0·2N or less. It could also be formed by heating solutions of low acidity. Kraus and Nelson [2] mention the colloid in general terms, comparing it with similar colloids formed by quadrivalent zirconium, uranium, and cerium. Work was also done at Harwell in 1950 by Hurst, Hall, Herniman, and Walter. The formation of the colloid and its absorption spectrum were studied but the results were not published.

In 1954 the production and some properties of colloidal plutonium(IV) in somewhat greater detail were described.[3] The characteristic maxima of the detailed absorption spectrum were given, together with a description of its absorptive properties, and various estimates of the molecular weight of the colloid particles. However, it was decided to investigate the preparation and properties of the colloid more thoroughly and if possible isolate the pure material by dialysis. The weak positive charge [3] of the colloid suggested ion exchange as another possible means of separation.

Solutions of colloidal plutonium(IV), also containing the ionic ter-, quadri-, and sexavalent states, were prepared by dilution of acid quadrivalent plutonium solutions with

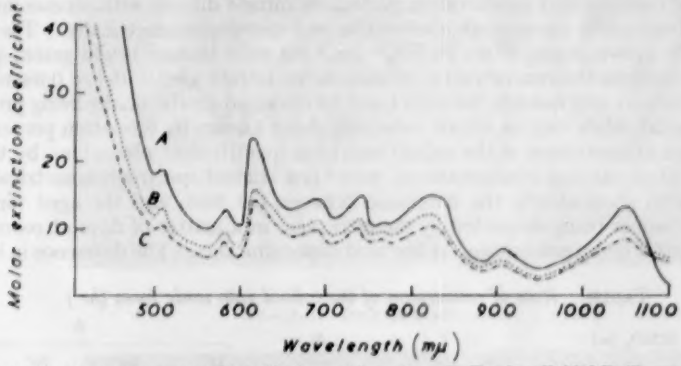
* Part IV, *J.*, 1956, 2565.

[1] "The Transuranium Elements," National Nuclear Energy Series, McGraw-Hill Book Co. Inc., New York, 1949, Vol. IV—14B, pp. 212, 215, 504, 572, 588.
[2] Kraus and Nelson, U.S.A.E.C., Declassified Document, A.E.C.D. 1888.
[3] "The Actinide Elements," National Nuclear Energy Series, McGraw-Hill Book Co. Inc., New York, 1954, Vol. IV—14A, p. 317.

water. Similar solutions, containing plutonium(IV) colloid which had aged for about six months, were also available.

Dialyses with either parchment or Cellophane membranes were only partly successful, and since the procedure was tedious it was abandoned in favour of ion-exchange. Use of Amberlite IR-120 in the hydrogen form provided solutions of colloidal plutonium(IV) free from other plutonium species, and this method of separation was used from then on. Attempts to determine the distribution ratio of the colloid by equilibration gave impossibly high values, probably owing to adsorption on the resin instead of exchange. Three solutions of pure colloidal plutonium(IV) were obtained by the ion-exchange method: a solution of

FIG. 1. *Absorption spectra.*



A, Aged colloidal Pu^{IV} prepared by dilution with water; *B*, Fresh colloidal Pu^{IV} prepared by dilution with water; *C*, Fresh colloidal Pu^{IV} prepared by dilution with aqueous ammonia.

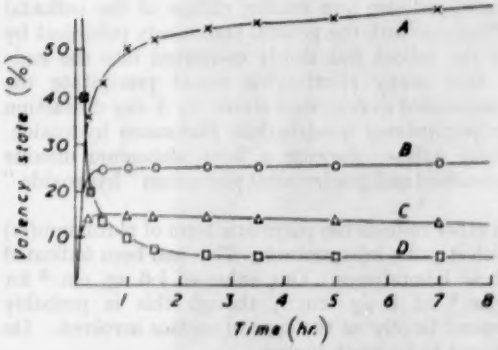


FIG. 2. *Equilibration of valency states of plutonium.*

A, Colloidal Pu^{IV}; *B*, Pu^{III}; *C*, Pu^{VI}; *D*, Pu^{IV}.

aged colloid, a solution freshly prepared by dilution with water, and another prepared by dilution with 0·1M aqueous ammonia.

The absorption spectra of these solutions are shown in Fig. 1. They are quite distinct from each other, but their shapes are the same, with corresponding absorption peaks at the same wavelengths. The method of preparation, and the age of the colloid, obviously affect the spectrum considerably. The American workers almost certainly isolated the pure material, probably by dialysis although no method was described, since the spectra found by them ($\lambda_{max.}$ 510, 579, 618, 817 mμ; Kraus [3]) are almost identical with ours ($\lambda_{max.}$ 510, 580, 615, 690, 740, 825, 910, and 1045 mμ).

Having established the complete absorption spectrum of fresh colloidal plutonium(IV) it became possible to measure its approximate rate of formation in a diluted quadrivalent plutonium solution. The spectra of all the ionic valency states of plutonium being well

established, the proportions of each were easily calculated. The results (Fig. 2) show that the colloid is formed extremely quickly in 0·1M-nitric acid, over 40% being formed in the first thirty minutes. Disproportionation $3Pu^{IV} \rightleftharpoons 2Pu^{III} + Pu^{VI}$ competes,[4] and after several hours the solution reaches an almost steady state with about 55% of colloidal quadrivalent plutonium, 25% of the tervalent state, and smaller amounts of the other valency states. Thereafter the proportion of colloidal plutonium(IV) increases very slowly to a maximum of about 75%.

It is well known that quadrivalent plutonium forms strong complexes with the nitrate ion,[5] a situation which would always tend to oppose formation of the colloid. In 0·1M-nitrate ion solutions the colloid is formed immediately and it was therefore decided to investigate its formation in solutions of low acidity and high nitrate concentration. Solutions of concentrated quadrivalent plutonium nitrate diluted with ammonium nitrate solutions of increasing concentration were examined spectrophotometrically. The solutions were initially brown, owing to the $PuNO_3^{3+}$ ion,[5] but most became bright green, quickly or slowly according to the concentration of ammonium nitrate used. Below 0·5M-nitrate ion the colloid formed very quickly, between 1 and 2M it formed slowly, finally being precipitated as a green solid, while only in nitrate solutions above 4M was its formation prevented.

The rates of conversion of the colloid into ionic quadrivalent plutonium, by the action of nitric acid of varying concentrations, were then studied spectrophotometrically. The results (Table) show clearly the difference between the fresh and the aged form of the colloid, the former being converted by the nitric acid in a matter of days at room temperature, the latter being precipitated at low acid concentrations. The difference in behaviour

TABLE. *Rate of conversion of the colloid into ionic form (hr.)*

HNO_3 (M)	1	3	5			
Temp.	—	—	18°	50°	70°	90°
Fresh colloid	120	90	24	—	—	—
Aged colloid	Precipitated	Precipitated	>200	10	4	2·5

of the two forms possibly lies in the increased size and smaller charge of the colloidal particles in the aged form. These results agree with the general statements published by the American workers, who found that the colloid was slowly converted into the ionic form by 1M-nitric acid and showed that many electrolytes would precipitate the colloid.[3] Examination of the colloid, precipitated as described above, by *X*-ray diffraction showed it to be very similar to freshly precipitated quadrivalent plutonium hydroxide. Both the *X*-ray patterns were extremely diffuse, showing a faint plutonium dioxide structure, suggesting that the precipitated colloid and quadrivalent plutonium "hydroxide" are just hydrated plutonium dioxides.

It was expected that in common with other colloids the polymeric form of plutonium(IV) would be adsorbed on surfaces with which it came into contact. This had been indicated by Carniglia [3] and was confirmed in these laboratories. Our value of 1·6 μg. cm.$^{-2}$ for glass agrees well with Carniglia's figure [3] of 1 μg. cm.$^{-2}$, though this is probably coincidental since the adsorption will depend largely on the type of surface involved. On steel, for example, the adsorption was found to be much higher.

It was thought that the colloid might behave optically like a true ionic solution and this was demonstrated (Fig. 3) by application of Beer's law and Lambert's law to both the fresh and the aged form. The two laws are obeyed by the colloid, in both its forms, but unfortunately this fact is of little use for accurate determination of the colloid since each solution would have different molar extinction coefficients at the wavelengths used.

The behaviour of the colloid towards solvent-extraction was examined by using solvents and conditions under which quadrivalent plutonium is extracted. Use of dibutylcarbitol (diethylene glycol dibutyl ether), trifluorothiophenoylacetone in benzene, and tributyl phosphate in kerosene under the appropriate conditions showed that extraction of the colloid, as expected, was negligible. In the case of tributyl phosphate, however, one

[4] Ref. 1, p. 295.
[5] Ref. 1, p. 388.

PLATE 1. Colloidal plutonium(IV). (×187.)

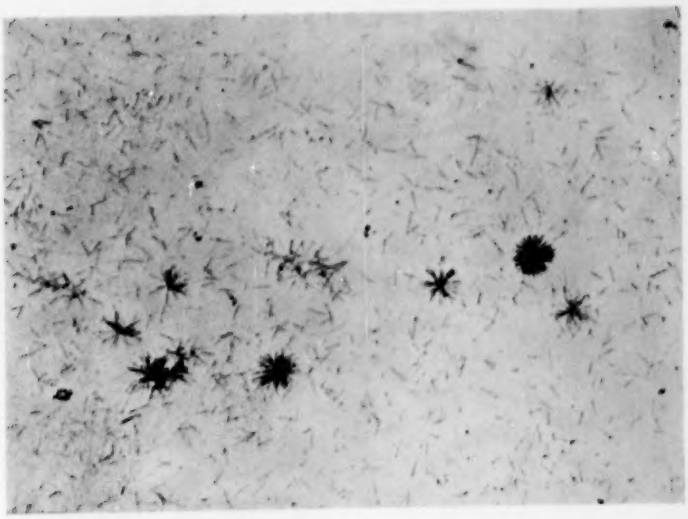
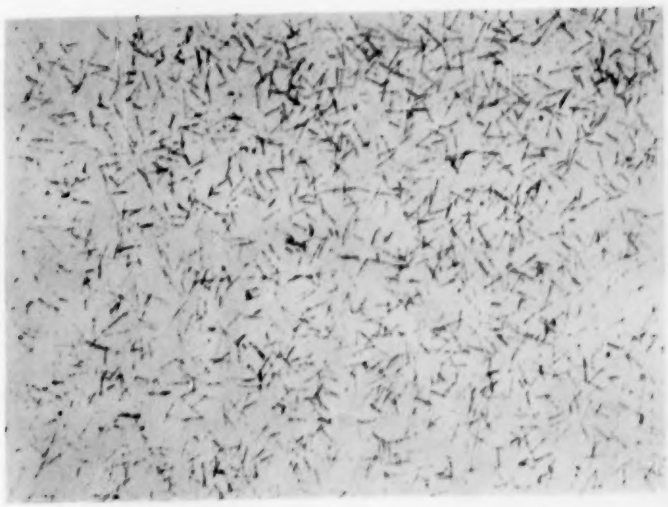


PLATE 2. Ionic plutonium(III). (×187.)

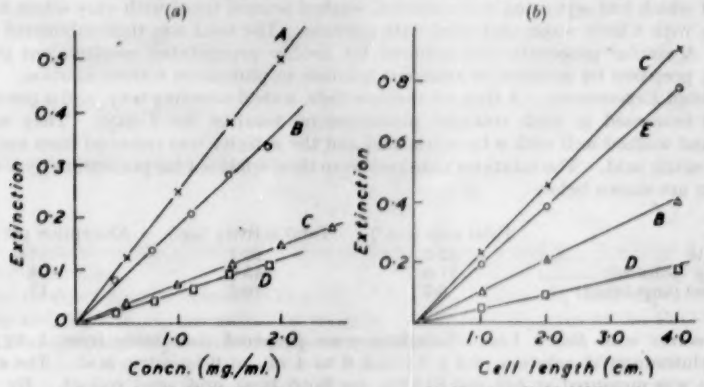


(*To face p.* 3350).

experiment gave a partition coefficient of **35**, due entirely to traces of dibutyl phosphate in the solvent. Further extraction experiments on the colloid in dilute acid with 5% dibutyl phosphate in kerosene gave high partition coefficients, the colloid entering the organic phase unchanged, as shown spectrophotometrically. It was also possible to extract colloidal ferric hydroxide into the same solvent with chloroform as a diluant. The mechanism of these extractions is not clear. In all experiments there was slight precipitation at the solvent–aqueous interface, the effect becoming very marked with aged colloid solutions.

High-speed centrifuge experiments (**7000** *g*) on solutions of aged polymer indicated that the molecular weight was extremely high, since most of the colloid could be centrifuged from solution in a few hours. A similar result was obtained with solutions of colloidal ferric hydroxide. The effect on solutions of fresh colloidal plutonium(IV) was very much less, only a very small fraction being centrifuged in the same time. Work with Ilford nuclear emulsion plates showed that the molecular weight of both forms was indeed very high. The colloid, obviously composed of particles of very different sizes, showed itself as characteristic "stars," each of which had been made by the α-particle tracks from

FIG. 3. *Conformance with* (*a*) *Beer's law and* (*b*) *Lambert's law.*



A, Aged colloid (440 mμ).
B, Fresh colloid (440 mμ).
C, Aged colloid (615 mμ).
D, Fresh colloid (615 mμ).
E, Aged colloid (510 mμ).

a single colloid particle (Plate 1). On the other hand, plates treated with ionic plutonium showed a completely random distribution of α-particle tracks (Plate 2). Calculations made from the number of tracks in the larger "stars" showed that the maximum molecular weight was of the order of 10^{10}. The fact that both the fresh and the aged form of colloidal plutonium(IV) gave similar results by the nuclear plate technique was unexpected. Possibly the aged form contains a much greater number of medium-sized particles which, although capable of being centrifuged, would not be detected by the nuclear plate technique.

The minimum molecular weight of the colloid was estimated by diffusion in an apparatus similar to that used by Anderson and Saddington.[6] The diffusion of fresh dilute colloid solutions was followed, ^{238}Pu being used as tracer. Comparison of this diffusion with that of a known ionic species,[4] $Pu(NO_3)_6^{2-}$, by use of the Graham–Riecke relation [6] showed that the minimum molecular weight was about 4000. These results show that the molecular weight of colloidal quadrivalent plutonium lies between extremes, and both the maximum (10^{10}) and minimum (4×10^3) figures are therefore only approximate. These values are well outside those quoted by American workers, who found values of $4{\cdot}2 \times 10^5$ by diffusion and 2×10^7 by ultracentrifugation. The method of preparation is possibly a factor in these differences.

[6] Anderson and Saddington, *J.*, 1949, S381.

Experimental

Apparatus.—Spectrophotometric measurements were made with a Hilger "Uvispek" spectrophotometer, 1 cm. glass cells being used except where stated. Water was used as the control.

Preparation and Purification of Colloidal Solutions.—All solutions were prepared by dilution with water of quadrivalent plutonium nitrate in nitric acid. This procedure gave solutions of the correct acidity (0·1M) at concentrations (1—3 mg./ml.) suitable for spectrophotometric analysis. The aged solutions were kept for a long period before purification.

The slow passage of a solution (10 ml.) down a 1 ml. burette packed with Amberlite IR-120 resin in the hydrogen form provided a solution of quadrivalent plutonium colloid which showed no detectable trace of other valency states. The concentration of each solution so prepared was found by α-particle counting. Solutions prepared in this way showed no change in concentration after further ion exchange.

Conversion of the Colloid into the Ionic Form.—A solution of colloidal plutonium(IV) (5 ml.) was diluted with nitric acid (9M) to give a solution of the required acidity. The spectral changes of the solution were then followed in a spectrophotometer.

X-Ray Examination of Precipitated Colloidal Plutonium.—Nitric acid (9M; 1·2 ml.) was added to a solution of the aged colloid (10 ml.) and the mixture well stirred. After 5 min. the light-green solid which had separated was collected, washed several times with very dilute nitric acid and finally with a little water and dried with acetone. The solid was then submitted to *X*-ray analysis. A similar procedure was followed for freshly precipitated quadrivalent plutonium hydroxide, prepared by addition of ammonia solution to plutonium nitrate solution.

Adsorption Experiments.—A thin microscope slide, a steel counting tray, and a piece of sheet steel were immersed in fresh colloidal plutonium(IV) solution for 7 days. They were then removed and washed well with 0·1M-nitric acid and the activity was removed from each sample by hot 5M-nitric acid. The solutions obtained were then analysed for plutonium by α-counting. The results are shown below:

	Total area (cm.²)	Total activity (μg.)	Absorption per cm.² (μg.)
Glass slide	12·5	20·1	1·6
Steel tray (polished)	11·0	45·0	4
Sheet steel (unpolished)	6·7	70·5	11

Conformance with Beer's Law.—Solutions were prepared containing from 1 to 5 ml. of colloidal plutonium(IV) solution (2·4 g./l.) and 0 to 4 ml. of 0·1M-nitric acid. The extinction of solution was measured at 440 and 615 mμ for both fresh and aged colloid. By using 1-, 2-, and 4-cm. cells it was shown that the polymer in both forms also obeyed Lambert's law.

Solvent-extraction Experiments.—Fresh colloidal plutonium(IV) solution was adjusted to the required acidity and the solvent equilibrated with an aqueous solution of the same acid strength. 1 ml. portions of each solution were shaken together in a stoppered tube for 10 min. The plutonium content of each layer was then determined by α-counting.

Solvent	Average Pu in solvent (μg.)	Average Pu in aqueous layer (μg.)	K
Diethylene glycol dibutyl ether	11·7	200	6×10^{-2}
0·2M-Trifluorothiophenoylacetone–benzene	7·7	1530	5×10^{-3}
20% Tributyl phosphate–kerosene	96	600	0·16
5% Dibutyl phosphate–kerosene	990	25	40

Estimation of Molecular Weight.—(a) *Centrifugation experiments.* Portions (3 ml.) of an aged colloid solution in a series of 5 ml. centrifuge tubes were centrifuged at 7000 *g* in a high-speed centrifuge for increasing periods. At the end of each period a tube was removed, the supernatant liquid removed, and the precipitated solid dissolved in nitric acid (8M). The plutonium content of this solution was then found by ordinary counting techniques. Both forms of the colloid were examined in this way, periods up to 5 hr. being used.

	Colloid centrifuged at 7000 *g* (%)				
Time (min.)	10	45	90	180	300
Aged colloid	7	30	55	75	85
Fresh colloid	—	—	—	—	5

(b) *Nuclear emulsion plate experiments.* Dilute solutions (10^{-7}M) were prepared of both the fresh and the aged colloid in 0·1M-nitric acid, as well as an ionic (tervalent) form of plutonium in 0·1M-hydrochloric acid. The nuclear emulsion plates (Ilford Type C.2, 50 μ) were immersed in each solution for 10 min., washed with very dilute acid, dried, and stored in the dark for several days. They were then processed and examined in a projection microscope. Photographs (Plate 1) were taken of the stars and " clumps " formed by the colloid particles, together with the random α-tracks shown by ionic plutonium (Plate 2). After allowance for a geometry factor of 3 it was seen that an average large colloid particle had given about 60 α-particles in, say, 11 days. From the specific activity of plutonium ($1·4 \times 10^6$ disintegrations min.$^{-1}$ μg.$^{-1}$) and Avogadro's number the molecular weight was calculated to be about 10^{10}.

(c) *Diffusion experiments.* An apparatus similar to that used by Anderson and Saddington [6] was constructed, with capillaries 2 cm. in length and 1·5 mm. in internal diameter. Colloid solutions were used which contained about 1 μg. of plutonium/ml.; the solution placed in the capillaries contained 90-year ^{238}Pu, which, while giving an appreciable α-count, was in negligible concentration. The diffusion apparatus was kept for 20 days in an insulated box and the change in the ^{238}Pu : ^{239}Pu ratio (caused by the diffusion of the " tagged " colloid *out* of the capillaries and the diffusion *in* of normal colloid from the surrounding bulk solution) followed by means of an α-pulse amplitude analyser. A similar experiment was performed using plutonium solutions in 8M-nitric acid. The results are as follows:

Species	Time of diffusion (hr.)	^{239}Pu (%)	^{238}Pu (%)	γ
$Pu(NO_3)_6^{2-}$	0	25 ± 1	75 ± 2	0·05
	620	96 ± 4	4 ± 1	
Colloid	0	17 ± 0·7	83 ± 2	0·98
	500	19 ± 0·7	81 ± 2	

The diffusion coefficient, is given by

$$D = \frac{4l^2}{\pi^2 t} \ln \frac{8}{\pi^2 \gamma} \text{ (ref. 6)}$$

where l = length of capillary (cm.), t = time of diffusion (sec.), and γ = fraction of tracer left in capillary after time t.

By the Graham–Riecke relation, $D_1\sqrt{M_1} = D_2\sqrt{M_2}$, where D_1 and D_1 are diffusion coefficients and M_1 and M_2 are molecular weights. If D_1 and M_1 refer to the $Pu(NO_3)_6^{2-}$ ion ($M_1 = 612$) and D_2 and M_2 to colloidal plutonium, then

$$D_1/D_2 = \sqrt{M_2}/\sqrt{M_1} = (t_2 \log \gamma_2)/(t_1 \log \gamma_1)$$

Substitution of the appropriate values gives M_2 about 4000. This is obviously only the order of the minimum molecular weight.

We thank Mr. K. Saddington for a discussion on the diffusion experiment, Mr. R. Diggle for help with the nuclear emulsion plate experiments, and Mr. E. F. Kemp for his interest. Grateful acknowledgment is also made to the Managing Director of this Group for permission to publish the results.

United Kingdom Atomic Energy Authority (Industrial Group),
Windscale Works, Cumberland. [*Received, March 6th*, 1956.]

654. *The Absorption of Uncharged Molecules by Ion-exchange Resins.*

By D. Reichenberg and W. F. Wall.

Sorption of acetic, propionic, *n*-butyric, and benzoic acid, and of ethyl, *n*-propyl, and *n*-butyl alcohol, by sulphonated cross-linked polystyrene resins from aqueous solution at 25° is shown to be true and uniform absorption, and not confined to the surface of the resin particles. The distribution is influenced by, *inter alia*, the cationic form and degree of cross-linking of the resin, the chain length and polar group of the solute, and the concentration in solution. The operative factors are believed to be: (1) simple dissolution of the solute in the water present in the resin; (2) "salting-out" by the polar groups of the resin (the exact mechanism of this is not understood but it may be represented, in some cases, by the solvation of these polar groups); (3) London dispersion interactions between the hydrocarbon part of the organic solute and the benzene nuclei of the resin; (4) polar attractive interactions (in some cases); (5) an unidentified factor necessary to explain why, at high concentrations, the order of the molality ratios of acetic, propionic, and *n*-butyric acid is inverted, *n*-butyric acid being absorbed the least.

When an ion-exchange resin is brought into contact with a solution containing ions and/or uncharged molecules, any or all of the following processes may occur: (1) Ion-exchange; (2) absorption (or desorption) of solvent, usually water, by (or from) the resin; (3) penetration of electrolyte into the resin; and (4) absorption of uncharged molecules by the resin. The present paper is concerned with the last of these.

The sorption of non-electrolytes by ion-exchange resins appears to have been discovered by Bhatnagar, Kapur, and Puri [1] in 1936, only a year after the first wholly synthetic ion-exchange resins were prepared.[2a] Subsequent studies [2] enlarged our knowledge of this phenomenon particularly with respect to the effects with a wide variety of solutes. However, there appears to have been little or no systematic study of the effects arising from variation of the structure of the resin, and in particular, its degree of cross-linking. The present study was therefore undertaken primarily with this end in view. Other factors were also investigated, including the effects of varying the cationic form of the resin, and the chain length and polar group of the solute.

In the present work, three resins of the sulphonated polystyrene type, cross-linked with 5½, 10, and 15% of divinylbenzene (DVB) severally were used. These divinylbenzene contents are nominal since there is some uncertainty as to both the true composition of the copolymer and the amount of divinylbenzene that is actually effective in cross-linking. Nevertheless, reproducible correlations exist between the nominal divinylbenzene content and all the important properties of the resin, namely, swelling,[3] ion-exchange equilibria,[4] kinetics,[5] and degree of penetration of electrolytes into the resins.[3] The absorption of ethyl, *n*-propyl, and *n*-butyl alcohol from aqueous solution into these three resins (both hydrogen and sodium forms) have been measured at 25° at three concentrations. For acetic, propionic, and *n*-butyric acid it was only possible to use the hydrogen form of the resins (since ion-exchange would occur with other cationic forms). These acids too have been studied at three concentrations and, in addition, the absorption of acetic acid was studied down to very low concentrations (0·01m) and compared with that of benzoic acid at these concentrations. For the present purpose, all these carboxylic acids may be regarded as non-electrolytes since, even in aqueous solution of as low a concentration as 0·01m, only about 3%

[1] Bhatnagar, Kapur, and Puri, *J. Indian Chem. Soc.*, 1936, **13**, 679; cf. Bhatnagar, Kapur, and Bhatnagar, *ibid.*, 1939, **16**, 249, 261; 1940, **17**, 361.

[2] (*a*) Adams and Holmes, *J. Soc. Chem. Ind.*, 1935, **54**, 1; (*b*) Samuelson, *Ingen. Vetensk. Akad. Handl.*, 1945, No. 179, 24; Tolliday, Thompson, and Forman, *J. Soc. Leather Trades Chemists*, 1948, **32**, 291; Erler, *Z. analyt. Chem.*, 1949, **129**, 209; (*c*) 1951, **131**, 106; Gregor, Collins, and Pope, *J. Colloid Sci.*, 1951, **6**, 304; (*d*) Wheaton and Bauman, *Ann. New York Acad. Sci.*, 1953, **57**, 159.

[3] Pepper, Reichenberg, and Hale, *J.*, 1952, 3129.

[4] (*a*) Reichenberg, Pepper, and McCauley, *J.*, 1951, 493; (*b*) Reichenberg and McCauley, *J.*, 1955, 2741.

[5] Reichenberg, *J. Amer. Chem. Soc.*, 1953, **75**, 589.

of dissociation occurs. In the resin phase, with its high concentration of hydrogen ions, the dissociation of the carboxylic acids will be much less.

Experimental

Resins.—The preparation of this type of resin in spherical beads has been described earlier.[3,4] The 5½% and 15% divinylbenzene resins were identical with those used by Reichenberg and McCauley [4b] for the study of ion-exchange relative affinities. The 10% resin, although not identical with, was very similar to that used in this previous work. Table 1 gives details of the properties of the resins.

Table 1.

Nominal divinylbenzene content (%)	Particle diameter (swollen in water) (μ)	Specific capacity (mg.-equiv. per g. of dry H-form resin)	Wt. swelling: g. of water absorbed per amount of resin equiv. to 1 g. of dry H-form resin	
			H form	Na form
5½	180—280	5·40	1·49	1·26
10	220—320	5·30	0·84	0·73
15	190—310	5·24	0·60	0·53

Organic Solutes.—" AnalaR " glacial acetic acid was checked by titration and was used without further purification.

Commercial samples of propionic and *n*-butyric acid were purified by distillation. The purities were then checked by the refractive indices and by liquid–vapour chromatography.[6]

Ethyl alcohol was purified as described by Smith,[7] then checked for its density, refractive index, and b. p.

Commercial samples of *n*-propyl and *n*-butyl alcohol were boiled with lime, then fractionally distilled. The refractive indices, densities, and b. p.s agreed with accepted values.

Determination of Absorption of Solutes by Resins.—The method used was essentially similar to that described [3] for measuring the penetration of hydrogen chloride from aqueous solutions into ion-exchange resins. It permits simultaneous measurement of the uptake of both water and solute. Resin samples (each about 1 g. when swollen) were introduced into centrifuge sinter tubes and their amounts determined by conversion into the H-form, displacement with sodium chloride, and titration of the liberated acid with alkali. For an absorption measurement, the sample of resin was first converted into the desired cationic form and thoroughly washed with water. An aqueous solution containing the organic solute in known concentration was then passed through the column of resin until the resin was in sorption equilibrium with it, with respect both to water and the organic solute. This " conditioning " process was carried out in an air-thermostat at 25·0° ± 0·5°. Each experiment was repeated at the same flow-rate but with twice the volume of solution, in order to check for completeness of conditioning. The amounts of solution normally used contained at least 25 mmoles of solute; sometimes double this quantity was used. The conditioning period was always at least 4 hr. After the conditioning, the resin sample was centrifuged at 2000 r.p.m. for 30 min. at 25° and weighed. On the particular centrifuge used, 2000 r.p.m. corresponds to 340 *g* at the top of the resin bed and 380 *g* at the part in contact with the sinter. After the weighing, water was passed through the column of resin to wash out all the organic solute. The effluent was collected and analysed for the organic solute. For the carboxylic acids, this was done by titration with standard alkali and a mixed indicator of p_T 8·3. For the alcohols, the total effluent was made up to 100 ml. and the concentration of the resulting solution determined with a Rayleigh interference refractometer. From time to time, duplicate determinations of the exchange capacity of the resin samples were made to check against loss of resin. Also, blank experiments were run to determine the amounts of liquid remaining in the sinter and between the beads of resin after centrifuging.[3] Thus were calculated the amounts of water and of organic solute held by the resin when in equilibrium with the conditioning solution. By repeating this with conditioning solutions of various concentrations, complete absorption isotherms for 25° were obtained.

Results and Discussion

Careful consideration was given to whether the equilibrium amount of sorption was independent of the particle size of the resin. This was checked experimentally for sorption

[6] James and Martin, *Biochem. J.*, 1952, **50**, 679.
[7] Smith, *J.*, 1927, 1288.

from 2N-acetic acid. Table 2 shows that there is little or no effect of particle size on the sorption of either water or acetic acid and certainly no evidence in favour of decrease of sorption with increase of particle size. This proves that both the acetic acid and the water are uniformly *absorbed* throughout the interior of the resin particles and that *adsorption* on the surface of the particles plays a negligible part. This conclusion may also be drawn

TABLE 2. *Effect of particle size on the sorption of solvent and solute from 2N-acetic acid.*

Nominal divinylbenzene content (%)	5½		10		15	
Diam. of particles (swollen in water) (μ)	180—280	240—400	160—240	220—320	130—220	190—310
Acetic acid (mmoles) sorbed per g. of dry H-form resin	2·41	2·44	0·96	0·97	0·52	0·53
Water (g.) sorbed per g. of dry H-form resin	1·41	1·38	0·81	0·80	0·59	0·59

from the magnitude of the sorption of solute. In 0·5N-solution, the 15% resin (which sorbs the least) takes up 0·14 mmole of acetic acid per g. of the dry hydrogen-form resin. Even if the mean diameter of the swollen particles is assumed as low as 200 μ, adsorption would imply a surface concentration of about 23 molecules per Å² of the surface of the swollen resin particles. Even allowing acetic acid an area as low as 10 Å² per molecule, one would be compelled, on an adsorption basis, to postulate a multilayer 230 molecules deep. This is very much less probable than the concept of uniform absorption, even without evidence on the absence of any particle size effect. Since acetic acid is one of the least strongly sorbed solutes, uniform absorption may be taken as a general rule. It is

TABLE 3. *Absorption of water and organic solute from aqueous solutions of various concentrations.*

Solute	Form of resin	Molality in outside solution	E = wt. (g.) of H_2O absorbed *			G = amount (mmoles) of solute absorbed *		
			5½% DVB	10% DVB	15% DVB	5½% DVB	10% DVB	15% DVB
BzOH	H^+	0·0100	0·10	0·045	0·023	1·49	0·84	0·60
		0·0200	0·20	0·089	0·046	1·49	0·84	0·60
AcOH	H^+	0·0100	0·019	0·008	0·005	1·49	0·84	0·60
		0·0201	0·037	0·015	0·009	1·49	0·84	0·60
		0·0503	0·068	0·030	0·018	1·49	0·84	0·60
		0·101	0·13	0·059	0·034	1·48	0·84	0·60
		0·202	0·26	0·116	0·066	1·48	0·84	0·60
		0·514	0·64	0·27	0·14	1·46	0·83	0·59
		1·056	1·27	0·53	0·29	1·42	0·82	0·59
		2·234	2·41	0·97	0·53	1·35	0·80	0·58
Et·CO_2H ...	H^+	0·456	0·73	0·31	0·16	1·46	0·83	0·60
		0·941	1·45	0·54	0·28	1·43	0·82	0·59
		2·013	2·51	0·93	0·47	1·36	0·80	0·58
Pr·CO_2H ...	H^+	0·541	1·13	0·43	0·22	1·46	0·83	0·59
		1·134	1·95	0·74	0·33	1·42	0·82	0·59
		2·517	2·49	0·87	0·39	1·33	0·79	0·57
EtOH	H^+	0·519	0·83	0·41	0·26	1·46	0·83	0·59
		1·067	1·59	0·81	0·50	1·42	0·82	0·59
		2·262	2·88	1·43	0·89	1·34	0·79	0·58
	Na^+	0·519	0·44	0·23	0·14	1·22	0·71	0·52
		1·067	0·85	0·41	0·25	1·18	0·69	0·51
		2·262	1·81	0·74	0·51	1·09	0·64	0·48
PrOH	H^+	0·518	1·15	0·58	0·39	1·43	0·81	0·59
		1·075	2·33	1·12	0·73	1·36	0·79	0·57
		2·329	4·42	2·15	1·22	1·21	0·72	0·54
	Na^+	0·523	0·54	0·23	0·13	1·22	0·71	0·52
		1·084	1·01	0·42	0·24	1·18	0·69	0·51
		2·342	2·22	0·88	0·46	1·08	0·64	0·48
BuOH	H^+	0·210	0·60	0·30	0·17	1·44	0·82	0·60
		0·427	1·26	0·63	0·36	1·40	0·80	0·60
		0·886	2·68	1·27	0·74	1·29	0·76	0·59
	Na^+	0·210	0·29	0·13	0·06	1·23	0·72	0·53
		0·427	0·60	0·26	0·13	1·22	0·71	0·52
		0·886	1·37	0·60	0·30	1·15	0·70	0·51

* By 1 g. of dry H-form resin or an equiv. wt. of dry Na-form resin.

only when the total sorption is very low that the possibility of adsorption need be considered seriously. Such cases will arise mainly where the solute molecules are too large to penetrate easily the molecular pores of the cross-linked resin. Possible cases of such adsorption have been indicated by Davies and Thomas.[5]

Erler [2b] studied the sorption from aqueous solution of a number of organic acids on Wofatit F, a German resin of the phenolsulphonic type. He concluded that the sorption *increased* with increased particle size. This very surprising result is due to a fallacious experimental technique. Erler assumed, incorrectly, that after the solution had been shaken with resin for a few seconds there would be insufficient time for appreciable sorption to occur. He therefore calculated the total sorption from the difference between the titre (of an aliquot part) after 30 minutes' shaking and that after a few seconds' shaking. It is clear, therefore, that all his sorption values are too low, the error being greatest with the resins of the smallest particle size.

The results in Table 3 show that with each solute, at a given molality in the outside solution, the amounts of both water and solute absorbed by the resin decrease with increase

FIG. 1. *Absorption of acetic acid at 25° by the* H *forms of resins.*

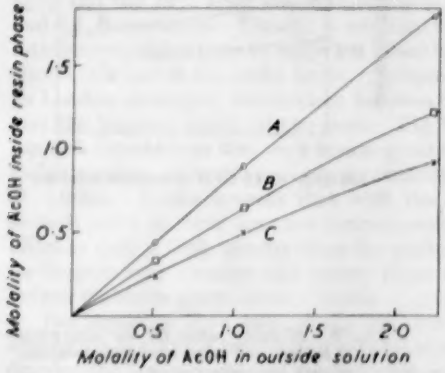
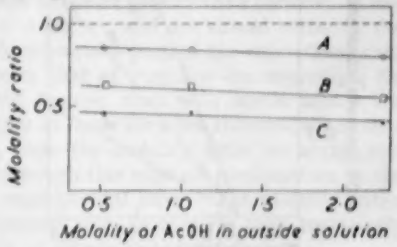


FIG. 2. *Molality ratios expressing the absorption of acetic acid at 25° by the* H *forms of resins.*



A, 5½% DVB; *B*, 10% DVB; *C*, 15% DVB.

of cross-linking of the resin. The simplest explanation is to suppose that the resin absorbs the water which in turn dissolves the solute. If there were no other effects, the molality of the solute (*i.e.*, mmoles per g. of water) inside the resin should depend on the molality in solution but be independent of the degree of cross-linking. Fig. 1 shows that for acetic acid the molality inside the resin depends markedly on the degree of cross-linking and this has been found also for all the solutes investigated. For subsequent representation, we define the " molality ratio " as the molality of solute inside the resin divided by the molality in the outside solution. This may be regarded as a partition coefficient between the aqueous phase in the resin and that in the outside solution. Fig. 2 shows the molality ratio for acetic acid plotted against the molality in the outside solution.

The concept mentioned above may be refined a little by considering the amounts of solute and " resin material " associated with 1 g. of water inside the resin for a given concentration of solute in the outside solution. As the cross-linking is increased, the amount of " resin material " increases and the amount of solute decreases. On the assumption that the simultaneous increase of resin material and decrease of solute are related as cause and effect, the resin material may be regarded as having a " salting-out " effect on the solute. The simplest interpretation of salting-out is that the ions of the salt interact with a certain number of the solvent molecules in some way that prevents these molecules from fulfilling their normal function. Thus solvation of ions leaves less " free " solvent molecules for the solute to dissolve in.

[5] Davies and Thomas, *J.*, 1951, 2624.

If 1 g. of dry H-form resin absorbs E mg.-equiv. of solute and G grams of water from a solution of molality m, the above hypothesis leads to the equation

$$E = am(G - G_0)$$

where G_0 is the number of grams of water withdrawn by solvation of the exchange groups of 1 g. of dry H-form resin. G_0 is related to n, the hydration number of the exchange

FIG. 3. *Test of the simple "hydration" theory, using data on the absorption of acetic acid.*

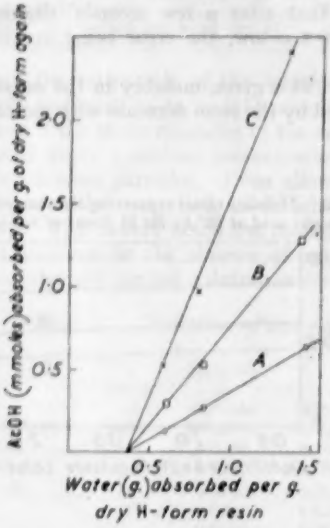


FIG. 4. *Molality ratios for the absorption of propionic acid by the H-forms of resins.*

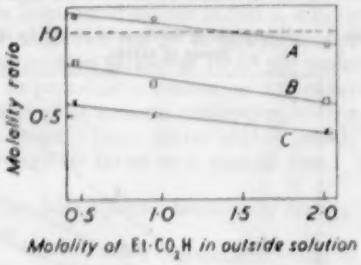


FIG. 5. *Molality ratios for the absorption of n-butyric acid by the H-forms of resins.*

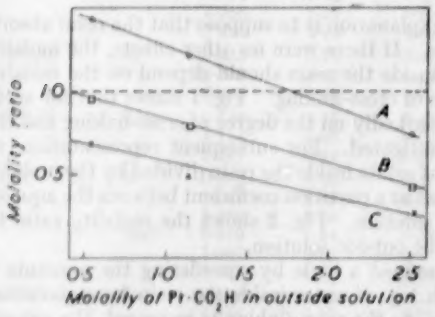
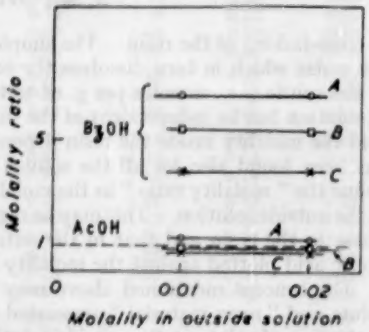


FIG. 6. *Molality ratios for the absorption of benzoic and acetic acid from solutions of very low concentration.*



For Fig. 3: *A*, 0·514m; *B*, 1·056m; *C*, 2·234m.

For Figs. 4–6: *A*, 5½% DVB; *B*, 10% DVB; *C*, 15% DVB.

groups of the resin, and n is assumed to be constant for a given solute and a given type of resin in a given cationic form. One may regard a as a rather abstract kind of partition coefficient representing the ratio of the molality of solute in the "free" water inside the resin to the molality in the outside solution. It may be noted that while the hypothesis involves the assumption that a is independent of the degree of cross-linking (at a given value of m) it does not involve assuming that a is independent of m (for a given degree of

cross-linking). This hypothesis predicts, therefore, that if, for each of a series of values of m, E is plotted against G, a series of straight lines should be obtained, all cutting the G-axis at the same value, G_0. The plot in Fig. 3 for acetic acid shows that all these expectations are fulfilled. The value of G_0 corresponds almost exactly to a hydration number of 4 for the sulphonic acid group, a plausible value. From the slopes of the straight lines, values of a may be deduced: for acetic acid, a is constant and independent of the molality (although this is not an essential part of the hypothesis) and is close to unity at all concentrations at least up to 2 m.

The simple hypothesis fits equally well for propionic acid and fairly well for *n*-butyric acid. Again G_0 corresponds to a hydration number of about 4. With propionic acid, a has a value 1·4, independent of the molality, but with *n*-butyric acid, a varies markedly with m, decreasing from about 2 at low molalities to slightly less than 1 at $m = 2{\cdot}5$m in the outside solution.

Fig. 4 shows that with the 10% and the 15% resin propionic acid has a lower molality inside the resin than outside at all concentrations, but with the 5½% resin the molality ratio is greater than unity at molalities below 1·4. With the 15% resin, *n*-butyric acid (Fig. 5) has a lower molality inside the resin than outside at all concentrations but with the 5½% and the 10% resin the molality ratio is greater than unity at molalities below 1·75 and 0·4, respectively. Clearly, in addition to the salting-out effects, there must be positive interactions which tend to make the molality inside the resin greater than outside. These effects increase in the order acetic < propionic < *n*-butyric and are almost certainly due to London dispersion interactions between the hydrocarbon part of the solute molecules and the benzene nuclei of the resin. Fig. 6 shows that at very low concentrations the London interactions are very much greater with benzoic than with acetic acid. The molality ratios for acetic acid are appreciably higher at these very low concentrations than at >0·5m. It also appears that with the 5½% resin the molality ratio for acetic acid exceeds unity at these very low concentrations, although this requires confirmation as the effect is only a little greater than the probable experimental error. The molality ratios for benzoic acid considerably exceed those for butyric acid, so that we may tentatively extend the series given above: acetic < propionic < *n*-butyric < benzoic.

The equation $E = am(G - G_0)$ also fits fairly well the experimental data for the absorption of ethyl, *n*-propyl, and *n*-butyl alcohol. Table 4 summarises results obtained by drawing the best straight line through each set of three points representing a given molality in the outside solution.

TABLE 4.

Solute	Form of resin	G_0	a	Concn. range (molality in outside solution)
AcOH	H^+	0·36	1·1	0·5—2·2
Et·CO_2H	H^+	0·35—0·40	1·4	0·5—2·0
Pr·CO_2H	H^+	0·38—0·43	2—1	0·5—2·5
EtOH	H^+	0·25	1·3	0·5—2·3
	Na^+	0·23	0·9	0·5—2·3
PrOH	H^+	0·24	2·0	0·5—2·3
	Na^+	0·28—0·31	1·2	0·5—2·3
BuOH	H^+	0·26—0·32	2·5—3	0·2—0·9
	Na^+	0·33	1·5—1·8	0·2—0·9

If a mean specific capacity of 5·3 mg. equiv. per g. of dry H-form resin is assumed, hydration numbers of 2, 3, 4, and 5 correspond with G_0 values of 0·191, 0·286, 0·382, and 0·478, respectively. Thus for the three acids with the resins in the hydrogen form, G_0 corresponds with a hydration number of 4. For the alcohols, G_0 corresponds more closely with a hydration number between 2 and 3, with both the hydrogen and the sodium forms of the resins: a possible reason for this is discussed below.

The most striking effect in connection with the absorption of alcohols is the effect of the cationic form of the resin. Fig. 7 shows that the hydrogen form of the 5½% resin absorbs *n*-butyl alcohol nearly twice as strongly as does the sodium form. This effect is exhibited also by the 10% and the 15% resin and applies also to ethyl and *n*-propyl alcohol.

Fig. 8 shows that for acetic, propionic, and butyric acid at low molalities the absorption increases with chain length, though this effect diminishes with increasing concentration and is even reversed at high concentrations. Clearly yet another factor is operative, though its nature is not clear. It might perhaps be thought to correspond with the co-volume term in the van der Waals equation of state for gases. The intersection point for the molality ratios of propionic and *n*-butyric acid occurs at a molality of 2·0 in the outside solution (1·8 inside the resin) with the 5½% resin. This corresponds with about 0·5 molecule of solute per sulphonic acid group. It is reasonable to expect the size of the solute molecules to have some effect in this range. A possible objection is that similar plots for ethyl, *n*-propyl, and *n*-butyl alcohol with the 5½% resin in either the hydrogen (Fig. 9) or the sodium form show no sign of any such convergence even though in the former case the highest concentration of *n*-butyl alcohol in the resin corresponds to 0·5 molecule per sulphonic acid group and that of *n*-propyl alcohol to about 0·85 molecule. However, this

FIG. 7. *Molality ratios for the absorption of n-butyl alcohol by (A) the* H- *and (B) the* Na-*form of a 5½% DVB resin.*

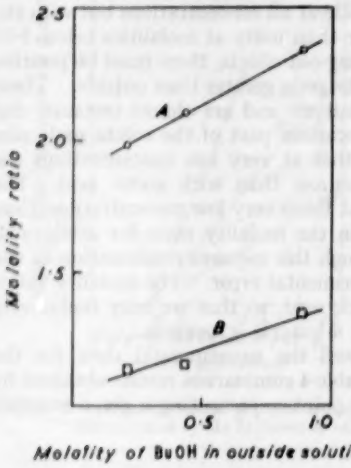
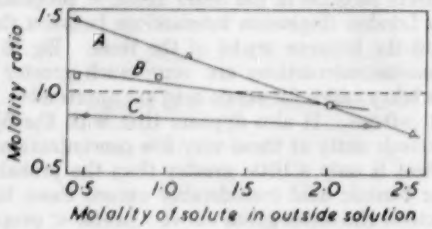


FIG. 8. *Molality ratios for the absorption of (A) acetic, (B) propionic, and (C) n-butyric acid by the* H-*form of a 5½% DVB resin.*



objection may not be conclusive since, as will be shown below, with the alcohols powerful polar interactions occur and these may mask the co-volume effect.

The effect of cross-linking may now be considered in more detail. Samuelson [25] showed that with a resin of very low cross-linking (*i.e.*, very high swelling) the molality of acetic or *n*-butyric acid inside the resin phase was the same as in the outside solution. This might be expected since, relatively to the amount of water present, the amounts of both the polar groups and the hydrocarbon matrix of the resin are too small for salting-out effects, London dispersion interactions, or salting-in effects to be appreciable. In this discussion, therefore, it will be assumed that, for all solutes at all concentrations, the molality ratio is unity at extremely low degrees of cross-linking. As the cross-linking is increased, in some cases (acetic acid may be an example—see above), the molality ratio decreases immediately to values below unity for all concentrations. In other cases (*e.g.*, *n*-butyric acid and *n*-butyl alcohol) the molality ratio increases to values above unity (at least at low concentrations). This is clearly due to predominance of salting-in over the salting-out effects. At higher degrees of cross-linking, salting-out effects always predominate and (in this range) further increase of cross-linking always decreases the molality ratio. Certainly in some and probably in all cases, increase of cross-linking eventually reduces the molality ratio to below unity. Concentration also plays a part since, with a given solute and a resin of a given degree of cross-linking in a particular cationic form, increasing the concentration may alter the molality ratio from a value above unity to one below unity.

So for each solute at a given concentration there is an optimum degree of cross-linking at which the molality ratio is a maximum, provided, of course, that it can rise above unity at all.

The explanation of the very considerable increase in absorption of the alcohols on changing from the Na- to the H-form of the resin appears to lie in one or more of three possibilities: (1) The difference is due to the fact that the hydrogen forms of the resins swell more, *i.e.*, absorb more water. However, this difference of swelling is relatively small and it is difficult to see how it could cause the large difference in molality ratio by any direct effect. Further, the difference in swelling is probably due entirely to the difference in the hydration of the sodium and the hydrogen ions,[3,9] in which case the sodium

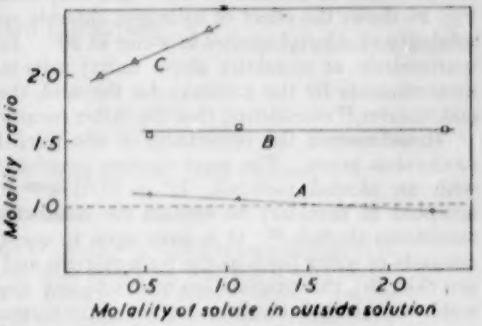


FIG. 9. *Molality ratios for the absorption of (A) ethyl, (B) n-propyl, and (C) n-butyl alcohol by the H-form of a 5½% DVB resin.*

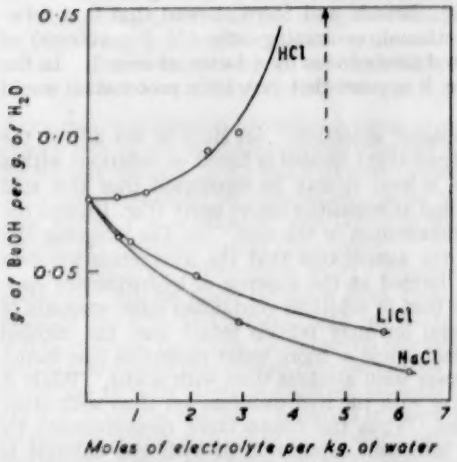


FIG. 10. *Effects of* NaCl, LiCl, *and* HCl *on the solubility of* n-*butyl alcohol in water at* 20°.

Aqueous solutions of HCl *of molality* 4·6 *and higher are miscible in all proportions with* n-*butyl alcohol at* 20°.

form of a resin would contain *more* "free" water than the hydrogen form. (2) If the sodium forms of the resins were completely ionized but the hydrogen forms only partly ionized, differences between the properties of the un-ionized SO_3H groups and the ionized $SO_3^-Na^+$ groups might be responsible for the effect. Thus there might be some form of polar interaction between the un-ionized SO_3H groups and the alcohol molecules. Or the un-ionized SO_3H groups might be incapable of salting-out the solute from the resin to the same extent as the ionized $SO_3^-H^+$ or $SO_3^-Na^+$ groups. This hypothesis is not implausible since, although sulphonic acids are generally regarded as "strong" acids, they are known to be not as strong as sulphuric acid, which in turn is not as strong as perchloric acid.[10]

[9] Reichenberg, *Research*, 1953, **6**, 98.
[10] Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, 1940, p. 261.

However, it is difficult to obtain reliably even an estimate of the dissociation constants of sulphonic acids in water. King and King [11] showed that, while the sulphonic acid group in sulphamic acid has a dissociation constant of only 0·1, in taurine the value is probably somewhat greater than unity. Taking this value of unity and neglecting activity coefficients, one calculates that only about 40% of the sulphonic acid groups would be ionized in the 5½% divinylbenzene resin and less in the resins of higher cross-linking. The calculation is crude and further discussion of this possibility is inhibited by lack of relevant data. (3) The most attractive hypothesis is that the difference in absorption is due mainly or entirely to the difference between the properties of sodium and hydrogen ions. Evidence for this is provided by the fact that hydrochloric and other strong acids markedly increase the solubility of alcohols in water and may ultimately make them completely miscible.[12] Fig. 10 shows the effect of hydrogen chloride and of lithium and sodium chloride on the solubility of *n*-butyl alcohol in water at 20°. Both salts salt-out markedly while the acid (particularly at molalities above unity) salts-in equally markedly (Fig. 10 is based on measurements by the authors; for the acid, these agree fairly well with those of Reburn and Shearer,[12] considering that the latter measurements were carried out at 25°).

If we assume the correctness of the third hypothesis, the question of the detailed mechanism arises. The most obvious possibility is the direct co-ordination of a proton with an alcohol molecule, $H^+ + ROH \rightleftharpoons ROH_2^+$. This mechanism is commonly accepted as necessary to explain the conductivity of solutions of hydrogen chloride in anhydrous alcohols.[13] It is more open to question whether, in systems containing large amounts of water (such as the resin systems and the system *n*-butyl alcohol–water–hydrogen chloride), this protonation occurs to any appreciable extent. The relative basicity of water and alcohols has been a point of controversy for some years (see Remick [14]). However, the most reliable recent work [15] indicates that the intrinsic basicity of water considerably exceeds that of ethyl alcohol. *E.g.*, Braude and Stern showed that in a 0·1M-solution of hydrogen chloride in aqueous ethanol, containing only 1% (by volume) of water, hydroxonium ions exceeded protonated alcohol ions by a factor of over 7. In the presence of large amounts of water, therefore, it appears that very little protonation would occur.

Two comments may be made on this apparent objection: (*a*) Most (if not all) of the evidence that water is more strongly basic than ethyl alcohol is based on solutions with a hydrogen chloride concentration of 1 molar or less; it may be significant that this acid only shows a salting-in effect on *n*-butyl alcohol at molalities above unity (Fig. 10) and the effect increases markedly with increasing concentration of the acid. (*b*) The foregoing discussion and objection have been based on the assumption that the interaction involves protonated alcohol ions which can only be formed at the expense of hydroxonium ions. However, there is the alternative possibility that in solutions containing large amounts of water (or inside the resins) the hydroxonium ion may remain intact and the alcohol molecule may enter its solvation shell, displacing one or more water molecules (the values of G_0 in Table 4 support this view, being lower with alcohols than with acids). While it is not easy to see why this should occur more with the hydroxonium ion than with other cations, there is some evidence that it does. Thus the conductance measurements by Bezman and Verhoek [15] indicate that the interionic separation of hydrogen chloride is much greater in ethanol solutions containing 2 moles of water per l. than in either water or ethanol solutions, whereas the interionic separation of ammonium chloride varies very little over the whole range of water–ethanol compositions. It is quite possible that, for some reason, alcohol molecules interact more strongly with hydroxonium ions than with other cations.

[11] E. J. King and G. W. King, *J. Amer. Chem. Soc.*, 1952, **74**, 1212; E. J. King, *ibid.*, 1953, **75**, 2204.
[12] Lieben and Rossi, *Annalen*, 1871, **158**, 137; Orton and Jones, *J.*, 1910, **115**, 1194; Reburn and Shearer, *J. Amer. Chem. Soc.*, 1933, **55**, 1774.
[13] Glasstone, "Introduction to Electrochemistry," Van Nostrand, New York, 1942, p. 13.
[14] Remick, "Electronic Interpretations of Organic Chemistry," John Wiley, New York, 2nd Edn., 1949, pp. 252—259.
[15] Braude, *J.*, 1948, 1971; Braude and Stern, *J.*, 1948, 1976; Bezman and Verhoek, *J. Amer. Chem. Soc.*, 1945, **67**, 1330.

It is of interest that polar interactions of a positive kind (as opposed to salting-out effects) are not confined to the alcohols. Thus Wheaton and Bauman [24] showed that the hydrogen form of a sulphonic acid resin cross-linked with 8% of divinylbenzene absorbed acetone about twice as strongly as formaldehyde. The sulphate form of a strong-base anion-exchange resin of the same cross-linking (8%) absorbed formaldehyde nearly twice as strongly as acetone, while the chloride form of a similar anion-exchange resin (of 7·5% divinylbenzene) absorbed formaldehyde and acetone to nearly the same extent.

This work was carried out as part of the research programme of the Chemical Research Laboratory and is published by permission of the Director. The authors thank Dr. A. J. P. Martin and Dr. A. T. James for kindly checking the purity of samples of propionic and *n*-butyric acid by liquid–vapour chromatography.

High Polymers Group, Chemical Research Laboratory,
Teddington, Middlesex. [*Received, March 8th*, 1956.]

---

655. *Structure and Reactivity of the Oxy-anions of Transition Metals. Part I. The Manganese Oxy-anions.*

By A. Carrington and M. C. R. Symons.

The electrode potential of the MnO_4^-–MnO_4^{2-} couple has been measured in aqueous alkaline solution at various ionic strengths, and the results extrapolated to give an E° value of 0·558 ± 0·002 v. The MnO_4^{2-}–MnO_4^{3-} couple has been studied in concentrated aqueous potassium hydroxide solution and a value of 0·285 ± 0·010 v found for the electrode potential adjusted to equal concentrations of the manganese ions at ionic strengths between 6 and 12. Some general observations on the reactivity of the manganate and hypomanganate ions are made, and the visible and ultraviolet absorption spectra of these ions in solution recorded.

Although considerable attention is being given to the structure and properties of complex compounds of the transition metals, the oxy-anions, in which the metal frequently shows its highest valency, have received little attention. This work will be concerned largely with transition-metal oxy-anions of general formula XO_4^{y-}, but condensed forms of these ions will also be considered, and later the work will be extended to anions in which the ligands are hydroxyl rather than oxide.

In considering structure it will be assumed that the ion XO_4^{y-} is tetrahedral and an endeavour will be made to throw light upon the electronic structure by detailed examination of electronic and paramagnetic resonance spectra.* In studying reactivity, attention will be confined to certain fundamental reactions for which, from measurements of electrode potentials, overall free-energy changes can be calculated. These reactions will be classified according to their mechanism either as electron-transfer or as displacement reactions with the aid of kinetic studies. Included in these reactions of transition-metal oxy-anions will be their oxidation and reduction by water and hydrogen peroxide, their disproportionation and condensation, and their ability to exchange oxygen.

In this paper we report measurements of the visible and ultraviolet absorption spectra of permanganate, manganate, and hypomanganate ions in aqueous solution, the electrode potentials of the permanganate–manganate and manganate–hypomanganate couples, and certain aspects of the reactivity of these ions. These topics are considered in turn.

Absorption spectra

Experimental.—Water used was doubly distilled from a concentrated alkaline solution of potassium permanganate, and glassware was cleaned with a similar solution. "AnalaR" reagents were used throughout.

* The paramagnetic resonance studies are being made in conjunction with Dr. D. J. E. Ingram.

Spectrophotometric measurements were made using a Unicam SP 600 spectrophotometer for the range 1000—360 mμ and a Unicam SP 500 spectrophotometer for the range 360—200 mμ. Calibrated quartz cells of 1 mm. thickness and stoppered quartz cells of 1 cm. thickness were used. When necessary, test solutions were compared with solutions of potassium hydroxide of the appropriate concentration.

Potassium manganate was prepared by heating at 120° a solution of potassium permanganate in aqueous 8M-potassium hydroxide until a clear green colour was produced. The solid potassium manganate formed on cooling was recrystallised from the same solvent. Hydrated sodium hypomanganate was prepared by a modification of Lux's procedure.[1] Slightly less than 1 equiv. of powdered sodium sulphite was added to a solution of potassium manganate in aqueous sodium hydroxide (12M), and the solution cooled in ice until dark blue needles of the hydrated salt were deposited.

Potassium permanganate solutions were prepared by dissolving the solid in water containing a trace of perchloric acid to prevent decomposition. The concentrations were determined by titration with standard aqueous oxalic acid. These permanganate solutions were stable for many months if kept in the dark. Manganate solutions were prepared either by heating a permanganate solution of known concentration containing potassium hydroxide (4M), or by dissolving recrystallised potassium manganate in aqueous potassium hydroxide (4M). These solutions were stable in stoppered bottles for several weeks. Hypomanganate solutions were

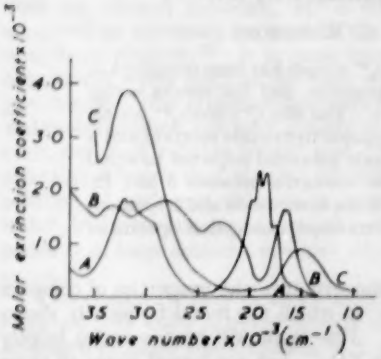


FIG. 1. *Visible and ultraviolet absorption spectra of the manganese oxy-ions.*
A, MnO_4^-. *B*, MnO_4^{2-}. *C*, MnO_4^{3-}.

prepared either by heating a permanganate solution of known concentration containing potassium hydroxide (12M), or by dissolving sodium hypomanganate in aqueous potassium hydroxide solution (12M). These solutions were stable for 2—3 days and then decomposed rapidly.

Neither addition of inert electrolytes nor temperature changes of the order of 50° had any noticeable effect on the permanganate spectrum. Further the spectra of the manganate and hypomanganate ions in solution were unaffected by limited changes in the concentration of alkali, and Beer's law was obeyed by solutions of both ions.

Attempts were made to estimate the concentrations of manganate and hypomanganate solutions by adding sufficient acid to cause complete disproportionation, centrifuging to remove manganese dioxide, and measuring the optical density of the remaining permanganate solution. This procedure gave low results, probably because the permanganate first formed decomposed slightly before all the alkali had been neutralised.

The spectra are shown in Fig. 1. These results were used for the estimation of mixtures of permanganate and manganate, spectrophotometric readings being taken at 417 mμ (23,980 cm.$^{-1}$) and 500 mμ (20,000 cm.$^{-1}$), and for the estimation of mixtures of manganate and hypomanganate, spectrophotometric readings being made at 434 mμ (23,050 cm.$^{-1}$) and 715 mμ (13,980 cm.$^{-1}$). Pairs of simultaneous equations involving these readings were solved to obtain the individual concentrations.

Discussion.—The absorption spectrum of potassium manganate in mixed crystals with potassium sulphate has been studied by Teltow [2] but we have found no record of its spectrum in solution. The spectrum of the hypomanganate ion has not been previously re-

[1] Lux, *Z. Naturforsch.*, 1946, **1**, 281.
[2] Teltow, *Z. phys. Chem.*, 1939, **44**, *B*, 74.

corded. The measurements of the absorption spectrum of the permanganate ion in solution, shown in Fig. 1, are consistent with many earlier measurements and agree precisely with those made recently by Zimmerman,[3] although the molar extinction coefficients are somewhat lower than those recorded by Lange and Schusterius.[4] A discussion of the significance of these spectra to the electronic structure of the ions is deferred to a later paper.

Electrode potentials

Experimental.—Potential measurements were made with the cell:

Satd. calomel electrode | Satd. KCl ¦ Manganese soln. | Platinum.

Oxygen-free nitrogen, previously passed over potassium hydroxide pellets, was bubbled continuously into the manganese half cell. The e.m.f. of the complete cell was balanced against that of a Weston standard cadmium cell by means of a Tinsley potentiometer and a sensitive spot galvanometer. Immediately after each e.m.f. measurement, the solution was analysed spectrophotometrically as described earlier, the estimated error being $\pm 1\%$. All e.m.f. measurements were made at 25° $\pm$0·5° and were reproducible to within 0·5 mv.

It was observed that the e.m.f. fell several mv quite rapidly immediately after the calomel electrode was placed in a concentrated alkaline solution, indicating the presence of a significant liquid-junction potential. In an attempt to avoid the uncertainty introduced, measurements were made with a mercury–mercuric oxide half cell in place of the calomel electrode. The half-reaction for this electrode is

$$HgO\ (red) + H_2O + 2e^- \rightleftharpoons Hg + 2OH^-;\ E^\circ = 0{\cdot}098\ v$$

The electrode was made by placing freshly distilled mercury into a small glass cup with a fused-in tungsten-wire contact, the mercury being then covered with mercuric oxide thoroughly wetted with the appropriate alkaline solution. The inside of the cup was covered with a thin film of Silicone grease to prevent the solvent creeping past the mercury. Measurements made with this electrode indicated that in 1m-potassium hydroxide the error due to the junction potential is well within the limits of experimental accuracy quoted. In 10m-potassium hydroxide, however, the junction potential appears to be of the order 10 mv and in 10m-sodium hydroxide to be as high as 40 mv.

Since permanganate is unstable in alkaline solution, the relative concentrations of permanganate and manganate in a given solution were continuously changing. Under the conditions chosen this rate was very slow, and by following the reaction spectrophotometrically and by e.m.f. measurements it was possible to cover a large range of relative permanganate–manganate concentrations at a given ionic strength. The values of E_o, obtained from the measured potentials E (adjusted to the hydrogen electrode scale) by use of the expression

$$E_o = E - (RT/nF)\ \ln\ (\text{oxidised form/reduced form})$$

differed by less than 1 mv, and this is taken as good evidence for complete reversibility. Because of this reproducibility only one of the many values obtained at a given ionic strength is recorded in Table 1. Complete reversibility would be expected for this couple since the only act at the platinum electrode is gain or loss of an electron, and electron exchange between permanganate and manganate ions in solution is known to be extremely rapid.[5] Similarly, the rapidity of the interaction between hypomanganate and permanganate ions in solution described later may be taken as evidence for reversibility of the manganate–hypomanganate couple, in accord with the fair reproducibility of results in solutions of high alkalinity.

In the study of the manganate–hypomanganate couple it was found that, after several hours, manganese dioxide was formed in the cell. It is thought that decomposition was induced by the platinum electrode, since comparable solutions in concentrated aqueous alkali kept in stoppered bottles were quite stable for several days. No measurements were considered under these conditions, and the marked drift in the e.m.f.'s which occurred was taken as a sensitive test for the formation of manganese dioxide.

Measurements of the permanganate–manganate and of the manganate–hypomanganate

[3] Zimmerman, *J. Chem. Phys.*, 1955, **23**, 825.
[4] Lange and Schusterius, *Z. phys. Chem.*, 1932, **159**, *A*, 295.
[5] Sheppard and Wahl, *J. Amer. Chem. Soc.*, 1953, **75**, 5133.

potential are shown in Table 1. The ionic strength, μ, was varied by changing the concentrations of sodium and potassium hydroxide, the contributions of the manganese ions being neglected. The potential of the calomel electrode was taken as 0·242 v.

TABLE 1. *Electrode potentials: (A) Hg–HgO electrode used in place of the calomel electrode; (B) measured in aqueous solution of sodium hydroxide in place of potassium hydroxide.*

	MnO_4^-–MnO_4^{2-} couple				MnO_4^{2-}–MnO_4^{3-} couple		
μ	$10^4[MnO_4^-]$	$10^4[MnO_4^{2-}]$	E_c (v)	μ	$10^4[MnO_4^{2-}]$	$10^4[MnO_4^{3-}]$	E_c (v)
4·0	3·71	2·81	0·595	12·0	0·61	1·27	0·287
3·0	2·60	1·32	0·592	10·0	0·72	1·17	0·279
2·0	1·47	0·94	0·586	10·0 (*A*, *B*)	0·58	1·64	0·370
1·0	3·54	4·97	0·583	10·0 (*B*)	0·58	1·64	0·330
0·83 (*A*)	2·96	2·31	0·580	8·8	0·38	0·91	0·282
0·75	6·80	2·70	0·579	7·5 (*A*)	1·08	0·83	0·294
0·56	4·41	2·50	0·577	7·5 (*A*, *B*)	0·65	1·50	0·310
0·32	2·30	1·94	0·575	6·0	2·75	0·13	0·285
0·24	1·70	1·54	0·573	4·0	1·77	0·22	0·301
0·06	0·46	0·82	0·567	3·0	5·07	0·42	0·303
0·02	0·79	0·69	0·565	2·0	0·87	0·21	0·328

Results and Discussion.—The value chosen for the permanganate–manganate couple is $E^\circ = 0{\cdot}558 \pm 0{\cdot}002$ v. In arriving at this value the graphical method of extrapolating

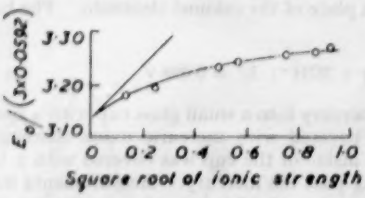


FIG. 2. $E_c/(3 \times 0{\cdot}0592)$ *for* MnO_4^-–MnO_4^{2-} *couple, plotted against the square root of ionic strength.*

potential measurements to zero ionic strength described by Randall and Vietti [6] has been used. This method has the advantage that the curve should approach a limiting line of slope 0·505 as shown in Fig. 2. Because the assumptions made in this method of extrapolation may be considered somewhat arbitrary, we have also applied the method used by Schumb, Sherrill, and Sweetser.[7] This gives an identical result within the limits quoted. Both these methods of extrapolation are described by Latimer,[8] who has estimated a value of 0·564 v for this couple. This was derived from the results given by Schlesinger and Siems,[9] using a value for the free energy of manganese dioxide which may be inappropriate since the thermodynamic properties of the dioxide vary with different samples. Our experiments are more direct, as they do not involve manganese dioxide, and therefore our value for E° will be used in preference to that of Latimer. The value of 0·58 v found by Miller and Rogers [10] from a polarographic study in 0·1M-aqueous sodium hydroxide is in fair agreement with our results.

No attempt can be made to extrapolate the results obtained for the manganate–hypomanganate couple to zero ionic strength. As the concentration of alkali was reduced to below 6M, the values of E_c increased markedly although a decrease would be expected. This is probably a result of partial protonation of the hypomanganate ion which, we postulate, would have a basicity similar to that of the orthophosphate ion. It might be argued that, since the chromate ion is a far stronger base than sulphate,[11] the hypomanganate ion should be far stronger than phosphate. If this were so, then the blue ion studied in these measurements would be $HMnO_4^{2-}$ and not MnO_4^{3-}. However, it is possible that the relatively high basicity of chromate is a consequence of the associated condensation to

[6] Randall and Vietti, *J. Amer. Chem. Soc.*, 1928, **50**, 1526.
[7] Schumb, Sherrill, and Sweetser, *ibid.*, 1937, **59**, 2360.
[8] Latimer, "The Oxidation States of the Elements and their Potentials in Aqueous Solutions," Prentice-Hall, Inc., New York, 1952.
[9] Schlesinger and Siems, *J. Amer. Chem. Soc.*, 1924, **46**, 1965.
[10] Miller and Rogers, *Science*, 1949, **109**, 61.
[11] Tong and King, *J. Amer. Chem. Soc.*, 1953, **75**, 6180.

dichromate and is thus apparent and not real. The constancy of our electrode-potential measurements in aqueous potassium hydroxide over a wide range of ionic strengths, and the fact that such hypomanganate solutions obey Beer's law, is evidence that MnO_4^{3-} is the only detectable species. Protonated species can only be present in minute concentrations.

The potentials measured in sodium hydroxide are consistently higher than in potassium hydroxide solution. This difference is also found in the relative reactivities of the two ions in sodium or potassium hydroxide solution, and is therefore real. However, as might be expected, the junction potential for the calomel electrode in aqueous sodium hydroxide appears to be large, whereas in potassium hydroxide solution it is always within experimental error. Therefore all the results obtained on using potassium hydroxide solutions in the range $\mu = 6$—12 have been averaged to give a value $0{\cdot}285 \pm 0{\cdot}010$ v, and, since the mercury–mercuric oxide electrode gave results somewhat higher than this, a value of 0·29 v is used for calculating the free energy of formation of the hypomanganate ion. This is used only when the free-energy change for a reaction involving manganate and hypomanganate in concentrated potassium hydroxide solution is being calculated. The value for the manganate–hypomanganate couple estimated by Miller and Rogers [10] in 0·1M-sodium hydroxide is far higher than our value and is probably spurious since they state that manganese dioxide was deposited on the electrode.

Reactivity

Only recently has it been realised that the blue solutions which can be derived from Mn^{IV} or Mn^{VI} under certain conditions, contain MnO_4^{3-} ions.[1] The fact that hypomanganate solutions can be made simply by heating manganate in concentrated alkaline solution,[12,13] and that the resulting blue solutions may then be heated to high temperatures for a long time without further change, is clear evidence that this ion is remarkably stable. However, for reasons discussed below, it is important when studying the reactivity of the hypomanganate ion to use conditions that preclude protonation, since the protonated ion readily undergoes disproportionation, and once manganese dioxide is formed the remaining hypomanganate decomposes rapidly. The formula MnO_3^- is sometimes used for the oxy-ion of Mn^V. Lux [1] has however shown that salts containing Mn^V are isomorphous with phosphates and vanadates. Crystals containing orthophosphate and Mn^V have been prepared in these laboratories for paramagnetic resonance studies, thus confirming the similarity of the phosphate and hypomanganate structures. The ion MnO_3^-, if it did exist, would probably be polymeric, and the observation that Beer's law is obeyed by the hypomanganate solutions used makes the occurrence of any equilibria involving condensed species improbable.

Experimental and Results.—Water and all reagents were purified as already described. Hydrogen peroxide was prepared by suitable dilution of the 90% unstabilised product supplied by Laporte Chemicals Limited. When necessary, concentrations of manganese oxy-ions were estimated spectrophotometrically. Reactions in hot concentrated alkaline solution were carried out in Pyrex tubes and thus a certain amount of dissolved silicate must always have been present. This procedure was considered preferable to one in which nickel, platinum, or silver crucibles were used since it was invariably found that some oxidation of the metal occurred

TABLE 2. *Estimated thermodynamic data for manganese oxy-ions.*

($S°$ values are calculated by means of Connick and Powell's formula.[14])

	$\Delta F°$ (kcal.)	$\Delta H°$ (kcal.)	$S°$ (cal./deg.)
MnO_4^- aq.	−107·4	−129·7	45·4
MnO_4^{2-} aq.	−120·3	−160·5	2·1
MnO_4^{3-} aq.	−127·0 *	−185·8	−44·6

* This value is not standard, but refers to MnO_4^{3-} in concentrated KOH solution.

[12] Symons, *J.*, 1953, 3956; 1954, 3676.
[13] Scholder, *Angew. Chem.*, 1953, **65**, 240.
[14] Connick and Powell, *J. Chem. Phys.*, 1953, **21**, 2206.

to give soluble salts. When oxygen-free conditions were required, the reactions were carried out *in vacuo*. However, it was generally found that simple heating in an open tube, in such a way that the upper part was filled with steam, was equally satisfactory.

Table 2 gives the estimated standard free energy, entropy, and heat-content values for the manganese oxy-anions. Table 3 shows the reactions under consideration, together with estimates for the overall free-energy and heat-content changes. Table 4 contains, in summary, the results found experimentally. These results will now be discussed in greater detail.

TABLE 3. *Some possible reactions of the manganese oxy-ions.*

ΔF_R° represents the free-energy change under standard conditions, with the one exception that ΔF° for MnO_4^{3-} is taken as $-127{\cdot}0$ (see above). ΔF_R° and ΔH_R° are calculated for $n = 1$, not for the equations as written. Other values for ΔF° and ΔH° are taken from Latimer,[8] except the value $-37{\cdot}4$ for ΔH° for the ion HO_2^-, which has been estimated from the value for the entropy S° given by Evans, Hush, and Uri (*Quart. Rev.*, 1952, **6**, 186). The values for equation (3) are the experimental results of Schlesinger and Siems,[9] and the ΔF° value for MnO_2 used in equation (4) has been derived from these results.

		ΔF_R°	ΔH_R°
(1)	$MnO_4^- + MnO_4^{3-} \rightleftharpoons 2MnO_4^{2-}$	$-6{\cdot}2$	$-5{\cdot}5$
(2)	$MnO_4^{2-} + Mn^{IV}$ (monomeric) $\rightleftharpoons 2MnO_4^{2-}$		
(3)	$3MnO_4^{2-} + 2H_2O \rightleftharpoons 2MnO_4^- + MnO_2 + 4OH^-$	$-0{\cdot}82$	$+7{\cdot}3$
(4)	$2MnO_4^{2-} + 2H_2O \rightleftharpoons MnO_4^{3-} + MnO_2 + 4OH^-$	$-14{\cdot}0$	$+3{\cdot}5$
(5)	$4MnO_4^- + 4OH^- \rightleftharpoons 4MnO_4^{3-} + 2H_2O + O_2$	$-3{\cdot}7$	$-10{\cdot}9$
(6)	$4MnO_4^{2-} + 4OH^- \rightleftharpoons 4MnO_4^{3-} + 2H_2O + O_2$	$+2{\cdot}6$	$-5{\cdot}4$
(7)	$2MnO_4^- + HO_2^- + OH^- \rightleftharpoons 2MnO_4^{2-} + H_2O + O_2$	$-14{\cdot}7$	$-20{\cdot}7$
(8)	$2MnO_4^{2-} + HO_2^- + H_2O \rightleftharpoons 2MnO_4^- + 3OH^-$	$-7{\cdot}4$	$+1{\cdot}2$
(9)	$2MnO_4^{2-} + HO_2^- + OH^- \rightleftharpoons 2MnO_4^{3-} + H_2O + O_2$	$-8{\cdot}5$	$-15{\cdot}2$
(10)	$2MnO_4^{3-} + HO_2^- + H_2O \rightleftharpoons 2MnO_4^{2-} + 3OH^-$	$-13{\cdot}6$	$-4{\cdot}4$

TABLE 4. *Observations on the reactions listed in Table 3.*

	Forward reaction			Reverse reaction		
	Speed	Temp.	$[OH^-]$	Speed	Temp.	$[OH^-]$
(1)	Rapid	20°	>6M	Not observed		
(2)	Not observed			Not observed		
(3)	Slow [a]	20	<1M	Rapid [b]	120°	>10M
(4)	Slow [a]	20	<10M	Rapid	100	>10M
(5)	Rapid	20	>10M	Not observed		
(6)	Slow	120	>10M [c]	Slow	120	>10M [d, e]
(7)	Rapid	20	> 5M	Not observed		
(8)	Not directly observed			Not directly observed		
(9)	Rapid	20	>10M	Not directly observed		
(10)	Rapid	120	>10M [e]	Not directly observed		

[a] Induction period. [b] Reaction proceeds *via* MnO_4^{3-}. [c] Oxygen continuously removed. [d] In presence of oxygen. [e] KOH, not NaOH.

General Discussion.—Reaction (1) was postulated earlier [12] and is immeasurably fast at room temperature. Reaction (2) has not yet been observed, but since any monomeric form of Mn^{IV} is likely to be derived from MnO_4^{3-} simply by electron-, and possibly proton-, transfer reactions and since reaction (1) is so rapid, the great stability of solutions of hypomanganate in concentrated alkali may be taken as evidence that this equilibrium is also far over to the right. The forward reaction (3) can be totally suppressed provided that the ratio of the concentrations of permanganate and manganate is above a specific value depending only on the concentration of alkali. However, even when permanganate is initially absent, a long induction period occurs before manganese dioxide is formed. Duke [15] studied this reaction kinetically but found somewhat shorter induction periods. This may have been because he prepared manganate by fusing permanganate with potassium hydroxide in a platinum crucible, a procedure which would almost certainly have yielded a considerable amount of hypomanganate. In discussing the mechanism of this reaction, both Duke [15] and Abel [16] appear to refer to manganese dioxide as if it could exist in solution as a monomer. It is far more likely that the formation of solid manganese dioxide is a polycondensation or displacement process, which, as in such reactions as polyesterification in

[15] Duke, *J. Phys. Chem.*, 1952, **56**, 882.
[16] Abel, *Monatsh.*, 1955, **86**, 461.

which the monomer has a functionality of three or more, would be expected to favour the ultimate separation of a closely knit three-dimensional polymer. This could then rearrange, at least in part, to give the more stable rutile structure characteristic of pyrolusite. It could also act as a reaction mediator for the equilibrium (3) or (4), since, provided the outermost manganese atoms retained their tetrahedral structure, the loss of permanganate ions from one site and the attachment of manganate ions at a different site should be rapid. Clearly, it is not necessary for monomeric Mn^{IV} to be formed before such condensation. If manganate resembles chromate, then some slight dimerisation would be expected at low alkaline concentrations, and ions such as $Mn_2O_7^{2-}$ might then act as centres of growth leading ultimately to the separation of manganese dioxide. This mechanism is still more probable for equilibrium (4), since hypomanganate will be a strong base and hence reactions of the type $2HMnO_4^{2-} \rightleftharpoons Mn_2O_7^{4-} + H_2O$ should occur more readily and at a higher pH. Also, this might be a cumulative process, since the highly charged ion $Mn_2O_7^{4-}$ should be a still stronger base, and hence such displacements will tend to occur preferentially on the growing polymer. At any stage in this process, manganate ions can split off, thus leaving Mn^{IV} in the polymer. There seems no compelling reason for postulating the formation of Mn^{III}.[15] It is therefore suggested that the induction period of the forward reactions (3) and (4), besides being sensitive to the concentration of alkali, will also be strongly dependent upon the initial concentration of manganate or hypomanganate. This is found to be the case, and alkaline solutions of hypomanganate can be kept for many days at room temperature provided the concentration is low ($<10^{-4}$M).

A mechanism for the decomposition of permanganate in alkaline solution to give manganate and oxygen [reaction (5)] has already been presented,[12] but has been disputed by Abel [16] and by Jezowska-Trzebiatowska, Nawojska, and Wronska.[17] For the present, however, this mechanism will still be used as a basis for discussion since the alternatives offered fail to explain certain characteristics of the reaction. Thus, by far the most striking feature of the kinetic results was the dependence of rate upon the initial concentration of permanganate. The mechanism suggested by Abel does not account for this dependence, which he suggests may be invalid. However, careful repetition has invariably given the same results. The relation derived by Abel from the results reported by Symons,[12] which shows that the initial velocity divided by the initial concentration of permanganate at a fixed concentration of alkali is a constant, is in fact in satisfactory agreement with both mechanisms. The rates reported by Jezowska-Trzebiatowska, Nawojska, and Wronska [17] are far higher than those observed under comparable conditions by Symons who, however, found that, unless very great care was observed in purifying the reagents and solvent, spurious kinetic results were obtained. Since these results were similar in form to those found by the Polish workers, it is tentatively suggested that this may account for the discrepancy. These authors also report kinetic results for the decomposition of manganate to hypomanganate and oxygen. Again the rates given are several orders of magnitude higher than we have observed. These authors conclude with a kinetic study of a reaction in which hypomanganate decomposes to give manganese dioxide and oxygen, but no evidence for this reaction has been obtained in these laboratories.

Reaction (6) has an unfavourable overall free-energy change and if it proceeds by a mechanism similar to that proposed for reaction (5),[12] it must also have a high energy of activation. It is therefore surprising that it may be induced to proceed in the forward direction. However, the reaction only occurs at high concentrations of alkali, under which conditions the reverse reaction is strongly inhibited, not only by the low solubility of oxygen in the medium but also because the relative concentration of water will be greatly diminished. (In 13M-alkali there are about four molecules of water to every hydroxide ion. Since the hydroxide ion will be strongly hydrated the effective concentration of water will be even smaller. The fact that sodium ions will be more strongly solvated than potassium ions may, in part, account for the marked differences observed for these ions.) Although reaction (8) is not directly observed, kinetic evidence for both the overall forward and the reverse step has been presented.[12]

[17] Jezowska-Trzebiatowska, Nawojska, and Wronska, *Bull. Acad. polon. Sci.*, 1954, **2**, 447.

The competing reactions (9) and (10) are the most interesting in this series. Since both reverse reactions are accompanied by a very large increase in free energy, they will be ignored. Two alternatives then arise. If the rate of (9) is much greater than that of (10), manganate will rapidly be converted into hypomanganate, and the hydrogen peroxide will then continue to decompose with no other apparent change. Conversely, if the rate of (10) is much greater than that of (9), then hypomanganate will at once be converted into manganate which will then catalytically decompose the peroxide. When a concentrated solution of sodium hydroxide is used as solvent, manganate is converted into hypomanganate under all conditions. Addition of further hydrogen peroxide merely results in rapid evolution of oxygen. If, however, a concentrated solution of potassium hydroxide is used, manganate is converted into hypomanganate at room temperature, but hypomanganate is converted into manganate at high temperatures, after which excess of hydrogen peroxide is catalytically decomposed without further change. That this remarkable difference is a function of temperature may be understood in terms of the estimated heat changes. Thus at low temperatures reaction (9) must be faster than (10). An increase in temperature favours the forward stage of reaction (10) more than that of reaction (9) so that at high temperatures reaction (10) dominates, and manganate is preferentially formed. The difference between the reactivity of manganate and hypomanganate in aqueous sodium or potassium hydroxide solutions parallels the differences found for the manganate–hypomanganate couple recorded above.

One of us (A. C.) thanks the Esso Petroleum Company for the award of a Post-graduate Research Studentship.

THE UNIVERSITY, SOUTHAMPTON. [*Received, March 13th*, 1956.]

---

656. *Molecular-weight Studies of Dextran.*

By G. C. BOOTH and V. GOLD.

A sample of a British dextran ("Intradex") has been fractionated by a precipitation method, and the molecular weights have been determined by osmotic-pressure, light-scattering, and viscosity measurements. Indirect tests of chain branching, based on the viscosity measurements, suggest that the dextran behaves as an unbranched coiled polymer in solution. Viscosity measurements on aqueous solutions of mixtures of dextran and bovine blood proteins do not reveal any interaction between these solutes.

IT is generally recognised that dextran is of variable composition. Extensive studies on its characterisation and molecular weight by a variety of physical measurements have been carried out in the United States,[1–5] chiefly on material synthesised by the bacterial strain NRRL-B512 of *Leuconostoc mesenteroides*, and in Sweden on Swedish dextran.[6] Some investigations have also dealt with physical measurements of British dextran, synthesised by the organism designated *Betacoccus arabinosaceous*, Birmingham,[7,8] but no corresponding correlation of molecular weights obtained by different methods has been published. The purchasing specification of the Ministry of Health lays down measurements of intrinsic viscosity and ease of excretion following intravenous injection in rabbits as criteria of the molecular-weight range of the sample. Neither of these properties is a

[1] Weissberg and Isbell, "Molecular Properties of Plasma Substitutes," Nat. Bur. Stand. Report 1713 (1952).
[2] Wolff, Mehltretter, Mellies, Watson, Hofreiter, Patrick, and Rist, *Ind. Eng. Chem.*, 1954, **46**, 370.
[3] Senti, Hellman, Ludwig, Babcock, Tobin, Glass, and Lamberts, *J. Polymer Sci.*, 1955, **17**, 527.
[4] Arond and Frank, *J. Phys. Chem.*, 1954, **58**, 953.
[5] Yang and Foster, *J. Polymer Sci.*, 1955, **18**, 1.
[6] Ingelman and Halling, *Arkiv Kemi*, 1949, **1**, 61.
[7] Ogston and Woods, *Trans. Faraday Soc.*, 1954, **50**, 635.
[8] Martin, *Chem. and Ind.*, 1955, 184.

direct indication of the molecular weight, although American [1-3] and Swedish [6] workers have published empirical correlations between intrinsic viscosities and molecular weights, as determined by other methods, for dextrans of American and Swedish origin respectively. However, the present studies seem to indicate that the dependence of intrinsic viscosity on molecular weight is different for dextrans of different origin and to confirm the American workers' warning that their viscosity–molecular-weight relation [1] applies only to materials resulting from the acid hydrolysis of native dextrans produced by the NRRL-B512 strain of *Leuconostoc mesenteroides*.

In the present work a specimen of a British clinical dextran ("Intradex") has been fractionated by a precipitation procedure closely similar to that used in the American studies.[1] The molecular weights of some of the fractions were determined by osmotic pressure and light-scattering methods. In addition, the intrinsic viscosities of all fractions

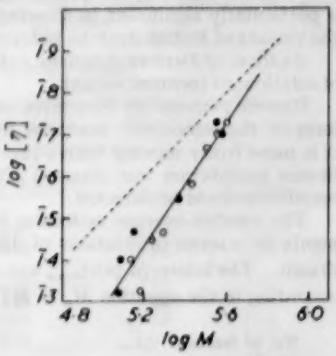


FIG. 1. *Relation between* log [η] *and* log *M*.

○ $\bar{M}_n$. ● $\bar{M}_w$. *The broken line shows the relation between* log [η] *and* log *M for* NRRL-B512 *dextran*.[1, 18]

were determined. These measurements enabled the formulation of an approximate empirical relation between intrinsic viscosity and molecular weight (Fig. 1) and hence, by interpolation, the determination of the molecular weights of all the fractions.

The viscosity measurements also allow some tentative conclusions about the structure of the dextran molecule in solution and its interaction with bovine blood proteins.

EXPERIMENTAL

Dextran was obtained in 1952 from Dextran Limited (Aycliffe, Co. Durham) (now part of Glaxo Laboratories Ltd.). Two specimens were employed in this investigation, both produced by the bacterial strain *Betacoccus arabinosaceous*, Birmingham: (i) Clinical dextran ("Intradex"), produced from a crude native polysaccharide by thermal degradation [9] and fractionally precipitated by acetone, fractions of high and low molecular weight being discarded. The intrinsic viscosity of the batch used was recorded by the firm at the time of its manufacture and was 0·35 decilitre g.$^{-1}$ at 37°, and the weight-average molecular weight was stated to be 175,000. It was supplied as a 6% solution, containing also 0·90% of sodium chloride. (ii) Natural polysaccharide from the same source.

Fractionation of Clinical Dextran.[1]—The complete contents of a 540 ml. bottle of "Intradex" were diluted to 2 l., with the addition of phenylmercuric acetate (0·1 g.) as fungicide. The solution was kept at 25° and methanol added in portions until the bulk of the liquid was permanently cloudy. The flask was then fitted with a mercury-sealed stirrer and heated at 45°. The heating bath was then allowed to cool slowly (36 hr.) to 25°. Stirring was stopped for 6 hr., during which the coacervate formed settled. The supernatant liquid was decanted, filtered through sintered glass, returned to the flask, and treated with more methanol to obtain the second fraction, and similarly for further fractions. The gel was dissolved in water and separated from the solution, in a spongy white and readily soluble form, by freeze-drying. The details of the main fractionation (B) [following a trial fractionation (A)] are given below.

[9] B.P. 719,382.

To obtain some fractions of high molecular weight, a sample of undegraded dextran was heated with aqueous hydrochloric acid, and the hydrolysate was subjected to a similar fractionation (specimen C).

No. of fraction	B1	B2	B3	B4	B5	B6	B7	B8	B9
Vol. % of methanol in soln. ...	45·6	46·7	47·7	49·0	50·3	51·7	53·8	56·9	76·4
Wt. of dry dextran in fraction	4·5	3·75	2·7	5·5	1·4	3·4	2·1	2·7	0·5

Unaccounted for : 5·8 g.

Infrared Spectra.—For identification the infrared spectra of Nujol mulls of undegraded dextran and of fractions A2b, A5, and B1 were determined on a Grubb–Parsons double-beam spectrometer. The bands observed in the diagnostically interesting region (768, 798, 846, and 917 cm.$^{-1}$) agree tolerably well with those reported [10] for dextran of the same origin (768, 793, 841, and 917 cm.$^{-1}$). The presence of the band at *ca.* 798 cm.$^{-1}$ (attributed to α-1 : 3-links [11]) is particularly significant in showing that the specimen of our investigation did not belong to the variant of British dextran isolated more recently.[12]

Analysis of Dextran Solutions.—This was carried out by freeze-drying, of measured amounts of solution, to constant weight.

Osmotic-pressure (π) *Measurements.*—These were carried out at 25° with a slightly modified form of the osmometer described by Weissberg.[13] *cyclo*Hexane was used in the capillary, as it is more freely moving than aqueous solutions. With suitably prepared nitrocellulose membranes equilibrium was attained after about 36 hr. and no diffusion of dextran through the membrane could be detected.

The number-average molecular weight ($\bar{M}_n$) of each fraction was calculated from measurements on a series of solutions of different concentrations (c). A graph of (π/c) against c was drawn. The intercept $(\pi/c)_{c\to 0}$ was obtained by linear extrapolation and used to calculate $\bar{M}_n$ according to the equation $\bar{M}_n = \boldsymbol{R}T[(\pi/c)_{c\to 0}]^{-1}$. The results are tabulated.

No. of fraction	A1	A2	A4	A5	B1	B5	B8
$10^{-3}\bar{M}_n$	384	269	172	136	394	195	153

Light Scattering.—The reduced intensity of scattered light (5461 Å) at an angle of 90° (R_{90}) was determined for dextran solutions with an apparatus of simple design constructed by Dr. P. M. Doty at the Royal Institution in 1947. A reading for the scattering of water was subtracted from all measurements. Care was taken to remove and exclude dust from all vessels and solutions. The apparatus was calibrated with purified benzene. The depolarisation was not measured and a depolarisation correction was not applied.

For each fraction of dextran studied a series of solutions was examined and a graph of (c/R_{90}) against c constructed. The intercept $(c/R_{90})_{c\to 0}$ was obtained by linear extrapolation and used to calculate the weight-average molecular weight ($\bar{M}_w$) from the equation $\bar{M}_w = [K(c/R_{90})_{c\to 0}]^{-1}$, where $K = (2\pi^2 n_0^2)(dn/dc)^2/\lambda^4 \boldsymbol{N}$ n_0 being the refractive index of the solvent and λ the wavelength of light used. The refractive-index increment (dn/dc) of solutions in the concentration range 0·19—0·84 g. per 100 g. of solution was found to be 0·148 g.$^{-1}$ ml. (cf. ref. 6). The results were :

No. of fraction	A1	A3	A5	B1	B5	B8
$10^{-3}\bar{M}_w$	362	236	121	356	142	118

Viscosity Measurements.—These were carried out at 25° in a Fitzsimmons suspended-level viscometer.[14] Intrinsic viscosities ($[\eta]$) were obtained as intercepts from graphs of $(\eta_{rel.} - 1)/c$ against c, from the definition $[\eta] = [(\eta_{rel.} - 1)/c]_{c\to 0} = [\eta_{sp.}/c]_{c\to 0}$, where $\eta_{rel.} = \eta_{soln.}/\eta_{solv.}$, and $\eta_{sp.} = (\eta_{rel.} - 1)$. The units of η are decilitres g.$^{-1}$, c being expressed as g. per 100 ml. of solution. From the slopes of these graphs, the Huggins constants k', defined according to the equation $(\eta_{rel.} - 1)/c = [\eta] + k'[\eta]^2 c$ were obtained. The results are tabulated.

[10] Barker, Bourne, Bruce, Neely, and Stacey, *J.*, 1954, 2395.
[11] Burket and Melvin, *Science*, 1952, **115**, 516.
[12] Barker, Bourne, James, Neely, and Stacey, *J.*, 1955, 2096.
[13] Weissberg, *J. Res. Nat. Bur. Stand.*, 1952, **49**, 393.
[14] Institute of Petroleum, Standard Methods of Testing Petroleum (1952).

Fraction	In H_2O at 25° $[\eta]$ (dl. g.$^{-1}$)	k'	In 40·5% aq. MeOH at 25° $[\eta]$	Fraction	In H_2O at 25° $[\eta]$ (dl. g.$^{-1}$)	k'	In 40·5% aq. MeOH at 25° $[\eta]$
A1	0·50	0·46	—	B6	0·28	0·18	—
A2	0·38	0·37	—	B7	0·26	0·58	—
A3	0·35	0·12	0·212	B8	0·21	0·67	0·145
A4	0·28	0·70	—	C1	1·07	0·79	—
A5	0·25	0·53	—	C2	0·54	0·43	—
B1	0·53	0·50	0·252	C3	0·31	0·43	—
B2	0·45	0·30	—	C4	0·20	0·73	—
B3	0·40	0·19	—	C1a	0·55	0·79	—
B4	0·38	0·20	—	C1b	0·83	0·70	—
B5	0·29	0·43	—	H	0·46	0·33	—

Viscosity measurements were also carried out on buffered aqueous solutions of some bovine blood proteins and their mixtures with dextran. A Table of results is given below. The calculated values of $\eta_{rel.}$ in the last column were obtained from the equation :

$$\eta_{rel.} = 1 + (\eta_{sp.}/c)_{protein} \cdot c_{protein} + (\eta_{sp.}/c)_{dextran} \cdot c_{dextran}$$

which is expected to apply if there is no interaction and each solute contributes independently to the relative viscosity of the solution. The relevant values of $(\eta_{sp.}/c)$ for the dextran fractions and proteins in the buffer solutions were found by independent experiments.

	$c_{dextran}$ (g./100 ml.)	$c_{protein}$ (g./100 ml.)	$\eta_{rel.}$	$\eta_{rel.}$ (calc.)
In buffer at pH 6·21				
Dextran A5	0·250	0·292	1·10	1·10
Bovine serum albumin	0·125	0·146	1·05	1·05
	0·370	0·353	1·36	1·39
Dextran C1a	0·246	0·236	1·23	1·23
Bovine fibrinogen	0·185	0·176	1·15	1·16
	0·095	0·088	1·07	1·07
In buffer at pH 7·47				
	0·360	0·336	1·69	1·66
Dextran C1a	0·240	0·223	1·41	1·38
Bovine globulin	0·120	0·167	1·29	1·28
	0·528	0·501	1·25	1·24
	0·349	0·334	1·17	1·15
Dextran A5	0·264	0·250	1·12	1·11
Bovine globulin	0·209	0·200	1·09	1·09
	0·174	0·167	1·08	1·07

The critical miscibility temperature for infinite molecular weight (Θ-point) was determined for 40·5% aqueous methanol from the equation $T_c = \Theta - b\Theta M^{-\frac{1}{3}}$, where T_c is the temperature at which cloudiness begins to appear (or disappear) on cooling (or warming) of a 6% or 15% solution of dextran. The Θ-point was found to be *ca.* 23° and is sufficiently close to 25° for the relative viscosity measurements in 40·5% methanol at 25° to be regarded as relating to the Θ-point.

Discussion

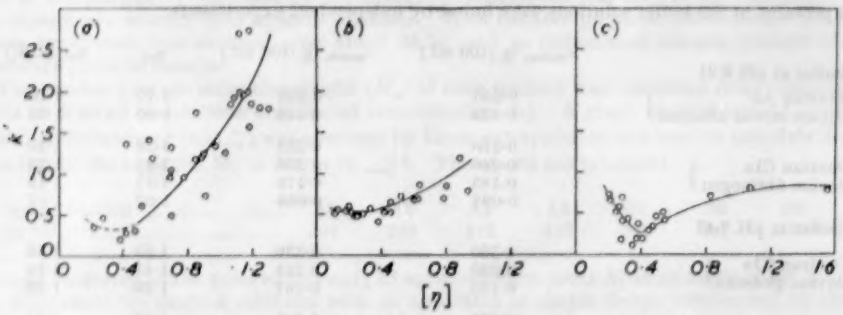
The intrinsic-viscosity determinations in 40·5% aqueous methanol allow a test for the occurrence of chain branching in the dextran molecule. According to the extension of the Flory–Fox [15] theory due to Wales, Marshall, and Weissberg [1,16] a value of less than 0·5 of the exponent a in the Mark equation $[\eta] = KM^a$, at the Θ-point, indicates chain branching, whereas the exponent has the value 0·5 for unbranched molecules. Our data lead to a value of a which is indistinguishable from 0·5 within the somewhat wide limits of experimental accuracy (*ca.* ± 0·1). The more precise data on NRRL-B512 dextran [1,16] lead to a value of 0·32. The index 0·32 indicates chain branching but it is not permissible,[1,16] on the theory mentioned, to invert the argument and regard the absence of chain branching as established for British dextran.

[15] Flory and Fox, *J. Amer. Chem. Soc.*, 1951, **73**, 1904.
[16] Wales, Marshall, and Weissberg, *J. Polymer Sci.*, 1953, **10**, 229.

Our viscosity measurements in aqueous solutions lead to the exponent 0·70 in the Mark equation, the maximum value of a being 0·8 for an unbranched coiled polymer, according to Flory and Fox's theory. This value compares with an exponent around 0·5 at low molecular weights [1,2] (and decreasing at higher molecular weight [5]) obtained for NRRL-B512 dextran and 0·34 for Swedish dextran.[6] According to Wales, Marshall, and Weissberg,[1,16] the intrinsic viscosity of hypothetical unbranched dextran is given by $[\eta] = 1{\cdot}99 \times 10^{-4} M^{0{\cdot}675}$ in the interval $11{,}000 < M < 370{,}000$. The exponent in this expression lies very close to our value but the numerical factor is too high to fit the results.

It is recognised as an empirical fact,[17] and with some theoretical justification,[18] that the relation between $[\eta]$ and the Huggins constant k' allows the detection and estimation of chain branching in polymer molecules. According to this test, a plot of k' against $[\eta]$ is horizontal for an unbranched polymer, whereas for a branched molecule k' increases with $[\eta]$ at high intrinsic viscosities. When k' is plotted against $[\eta]$ for dextran solutions (Fig. 2) it is found that k' for our specimen of British dextran increases less rapidly with $[\eta]$ than for Swedish dextran. American NRRL-B512 dextran again occupies an intermediate position. By analogy with other examples one may tentatively conclude that

FIG. 2. *Relation between intrinsic viscosity and Huggins constant k'.*



a, Swedish dextran.[6] *b,* NRRL-B512 *dextran.*[5] *c, "Intradex" (this work).*

Swedish dextran is the most highly branched, and British dextran the most nearly unbranched of the three types studied. None of the specimens gives rise to $[\eta]$–k' graphs of the precise shape found by Cragg and Fern [17] and, owing to the difficulties of precise viscometry on aqueous solutions, the experimental points from American,[1,3] Swedish,[6] and our work show a considerable scatter. Senti *et al.*[3] have suggested that k' passes through a minimum in the case of NRRL-B512, and we find that the same trend is perceptible in our own data and perhaps also in those of Ingelman and Halling.[6]

Our tentative conclusion that British dextran behaves as the most nearly unbranched of the three dextrans studied in this manner appears to conflict with the results of chemical methods which have shown British dextran from the same source to possess α-1 : 3-branches.[10] The two lines of evidence are not necessarily contradictory for, as Wales, Marshall, and Weissberg [1,16] point out, the frictional effect of branching will be lost and the molecule will behave like an unbranched chain if the branches are closely spaced so as to affect rotation about many bonds in the main chain. This could arise if the branch points occurred in small, closely packed groups. Possible structures of dextran, some of which follow this pattern, have been mentioned in the literature.[19]

The significance of molecular-weight determinations for clinical applications of dextran

[17] Speiser and Whittenberger, *J. Chem. Phys.*, 1945, **13**, 349; Walker and Winkler, *Canad. J. Res.*, 1950, **28**, *B*, 298; Manson and Cragg, *Canad. J. Chem.*, 1952, **30**, 482; Cragg and Manson, *J. Polymer Sci.*, 1952, **9**, 265; Cragg and Fern, *ibid.*, 1953, **10**, 185.

[18] Simha, *J. Res. Nat. Bur. Stand.*, 1944, **42**, 409.

[19] Dimler, Wolff, Sloan, and Rist, *J. Amer. Chem. Soc.*, 1955, **77**, 6568; Krysiak, Murawski, May, and Malec, *Acta Biochim. Polon.*, 1954, **1**, 27.

as a plasma-extender clearly depends on the extent to which measurements in aqueous solution reflect the true molecular weight of dextran particles in human blood. The problem awaits a more thorough study, but the exploratory experiments which we have carried out show that the interaction of dextran and bovine blood proteins is not detectable by viscosity measurements. In every case, the relative viscosity of a solution of a mixture of dextran and protein agreed with the value calculated by assuming independent contributions to the relative viscosity from the two solutes. The measurements therefore rule out the occurrence of appreciable association between dextran and bovine serum albumin, fibrinogen, and globulin.

The authors thank Sir Eric Rideal, F.R.S., at whose suggestion this investigation was undertaken, for his interest, and Dextran Ltd. and Glaxo Laboratories Ltd. for their co-operation in providing samples of dextran and information concerning them. The award (to G. C. B.) of the Daniell Scholarship by King's College, London, and of a State Scholarship is gratefully acknowledged.

KING'S COLLEGE, STRAND, LONDON, W.C.2. [*Received, March 23rd*, 1956.]

---

657. *The Polonium Halides. Part III.* Polonium Tetraiodide.*

By K. W. BAGNALL, R. W. M. D'EYE, and J. H. FREEMAN.

Polonium tetraiodide and cæsium hexaiodopolonite have been prepared and evidence for the existence of hexaiodopolonous acid has been obtained. The crystal structures of the cæsium salt and its tellurium analogue have been determined.

BURBAGE [1] reported that the attempted preparation of a polonium iodide from the elements was unsuccessful. By analogy with tellurium, a tetraiodide, and complex salts derived from it, would be expected to exist.

Polonium Tetraiodide.—Polonium tetraiodide is obtained as a black solid by the reaction of the elements at 1 mm. pressure at 40°, by treating polonium "hydroxide" or dioxide with 0·1N-hydriodic acid, by precipitation from solutions of polonium tetrachloride in dilute hydrochloric acid by 0·1N-hydriodic acid, or, as a black sublimate, when polonium dioxide is heated in dry hydrogen iodide at 200—250°. With dry hydrogen iodide in the cold polonium dioxide gives a black solid, which is probably an addition compound (PoO_2,xHI); this decomposes, when heated, into polonium tetraiodide and dioxide, and its X-ray powder photographs show no resemblance to those of the tetraiodide. Metallic polonium does not react with iodine in carbon tetrachloride, but an unidentified black solid is formed by the reaction of the metal with iodine in benzene.

The tetraiodide is slightly soluble in ethyl alcohol (1 g./l.) and in acetone, and is slowly hydrolysed to a white solid of indefinite composition in water. The hydrolysis products eventually become brown, probably owing to adsorbed iodine. The tetraiodide is insoluble in 2N-hydrochloric acid, N- or 2N-nitric acid, acetic acid, chloroform, benzene, carbon tetrachloride, and diethyl and dibutyl ether. It is decomposed by hot concentrated nitric acid or sodium hypochlorite solution, or slowly by concentrated potassium hydroxide solution. It is soluble in 2N-hydriodic acid, giving a solution which is red-brown at 20° and dark green at 0°; addition of a solution of cæsium iodide in 0·1N-hydriodic acid then yields an immediate precipitate of black cæsium hexaiodopolonite which is readily hydrolysed by water; the potassium and the rubidium salt are soluble.

Cæsium hexaiodopolonite decomposes at 200° *in vacuo*, yielding a black sublimate of polonium tetraiodide. Owing to the high volatility of the tetraiodide the vacuum thermal degradation technique used for the preparation of polonium dichloride and dibromide was unsuccessful.

The tetraiodide is reduced to the metal in warm gaseous hydrogen sulphide, and partly when sublimed in an X-ray capillary tube in a stream of nitrogen: as the sublimation proceeds,

* Part II, *J.*, 1955, 3959.

[1] Burbage, *Record Chem. Progr.*, 1953, **4**, 167.

a trail of the relatively involatile metallic polonium remains behind. There does not appear to be any reaction in hot gaseous ammonia.

Suspensions of the tetraiodide in 0·1N-hydriodic acid are not reduced by hydrazine or sulphur dioxide, even at the b. p., and no precipitate is obtained when dilute solutions of hydriodic acid or potassium iodide are added to solutions of polonium dichloride in hydrochloric acid.

Handling.—The techniques and hazards involved in handling curie amounts of polonium have been described in previous papers.[2] Preparations and reactions were carried out in *X*-ray capillaries.

Analysis.—The preliminary analyses were made by labelling specimens of the tetraiodide with ^{131}I of known specific activity. For example, a solution of potassium iodide (326 μg. of potassium iodide; 4 μc of ^{131}I/ml.) was added to polonium tetrachloride (100 μg.) in N-hydrochloric acid (0·5 ml.) in a micro-centrifuge cone. The precipitated polonium tetraiodide was washed with distilled water (4 × 0·1 ml.) and acetone (2 × 0·1 ml.), and the precipitate was made into a slurry with acetone on a glass counting-tray and allowed to dry. The polonium was then estimated by α-counting and the iodine by β-counting, due allowance being made for the decay of ^{131}I and for the γ-emission from the polonium. Owing to the volatility of polonium tetraiodide, the counting equipment became badly contaminated and was out of use for a prolonged period. The results were unsatisfactory (atomic ratio, I : Po, 3·3—5·6 : 1). A similar

FIG. 1. *Solubility of* PoI_4 *in aq.* HI *at* □ 0°; ○ 22°; △ 50°.

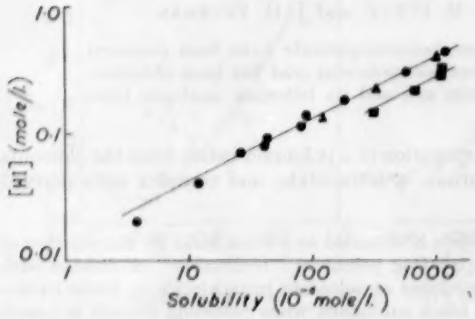
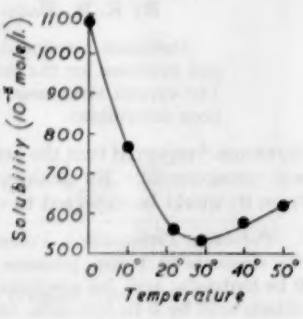


FIG. 2. *Solubility of* PoI_4 *in* 0·3N-HI.



procedure was used for a set of tracer experiments in which about 10^{-6} g. of the tetraiodide was sublimed before α- and β-counting (I : Po, 1·7—1·95 : 1).

Attempted liberation of iodine from the tetraiodide by chromic–sulphuric acid, acidified sodium nitrite, and oxygen at 150—200° was unsuccessful. In the first two reactions the tetraiodide is decomposed but the amount of iodine found was always low. The third resulted in formation of a white solid containing all the polonium and a variable proportion of the iodine: the composition of this product is unknown and *X*-ray powder photographs were complex.

Better results were obtained by suspending the tetraiodide in 20-vol. hydrogen peroxide (1 ml.), acidified with N-hydrochloric acid (1 ml.). After 10 min. the tetraiodide was completely converted into tetrachloride, and the iodine was extracted with carbon tetrachloride (3 × 2 ml.) and titrated against N/500-sodium thiosulphate; the polonium remaining in the aqueous phase was estimated by α-counting. The cæsium salt was identified by *X*-ray powder photography.

Solubility of Polonium Tetraiodide in Hydriodic Acid Solutions.—The solubility of polonium tetraiodide in 0·02—0·5N-hydriodic acid was determined from 0° to 50°. Fig. 1 shows the dependence of the solubility on acid concentration, from which it has been found that the solubility is proportional to the square of the acid concentration (the observed slopes are 1·99 at 20° and 1·96 at 50°).

The solubility was also determined in hydriodic acid–lithium iodide solutions of constant total iodide-ion concentration and varying hydrogen-ion concentration; the results show that the solubility is independent of the hydrogen-ion concentration and the reaction involved must therefore be

$$PoI_4 + 2I^- \rightleftharpoons PoI_6^{2-} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

[2] Bagnall, D'Eye, and Freeman, *J.*, 1955, 2320, 3959.

for which the equilibrium constant, $K_s = [PoI_6^{2-}]/[I^-]^2$, is $5{\cdot}9 \pm 0{\cdot}2 \times 10^{-3}$ at 22°. This relation does not hold for [HI] < 0·02N and it is possible that the deviations at low acid concentrations are due to the reaction

$$PoI_4 + I^- \rightleftharpoons PoI_5^- \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The equilibrium constant, $K'_s = [PoI_5^-]/[I^-]$, can be estimated by calculating the contribution to the solubility due to reaction (1) and subtracting the result from the observed value. This gives $K'_s = 6{\cdot}7 \pm 0{\cdot}5 \times 10^{-4}$ at 22°. A very large number of determinations of the solubility in very dilute (<0·01N) hydriodic acid were made using small (~10 μg.) amounts of the tetraiodide but the results were very inconsistent, presumably owing to hydrolysis of the tetraiodide as well as to radiolysis of the hydriodic acid.

The variation of the solubility with temperature is shown in Fig. 2; at 0°, 22°, and 50° the relation of solubility to acid concentration was found to be the same, so that the same complex ion is involved throughout.

Technique of solubility determinations. The polonium tetraiodide for these experiments was prepared by treating solid polonium tetrachloride (200 μg.) or freshly prepared polonium "hydroxide" with hydriodic acid (0·5 ml.) of the required concentration. The hydrochloric acid (~3×10^{-6} mole) liberated in the first reaction did not affect the solubility determinations. The resulting suspension of polonium tetraiodide in hydriodic acid was stirred in a small constant-temperature bath for 15 min. (experiments had shown that equilibrium was attained in this time), then transferred to a micro-filter-stick [3] (for determinations at 22°) or to a 1 cm. diameter, no. 4 filter-stick (for determinations at other temperatures) mounted in a 15 ml. centrifuge tube. The centrifuge tubes and filter sticks were kept in the thermostat until required. The temperature was maintained only within ±1°, since the heat contributions from the polonium invalidate precise control.

Hydriodic acid is rapidly oxidised by the intense α-bombardment and quantitative experiments with 400 mc samples of polonium gave a G value of 2·25 for the oxidation of this acid. Hence, in 15 minutes' contact time, 1 curie of polonium will oxidise 4×10^{18} molecules of hydriodic acid, equivalent to 13½% of the acid in 0·5 ml. of 0·1N-acid. Determinations of the solubility in more dilute acid could not therefore be made by this procedure.

In an alternative method the contact time was reduced as follows. About 100 μg. of polonium tetraiodide were precipitated in a micro-filter-stick and brought to the required temperature in the thermostat. Hydriodic acid of known concentration, and at the same temperature, was centrifuged through the pad of polonium tetraiodide, and the solution assayed for dissolved polonium. The procedure was repeated until the concentration of polonium in the acid solution became constant, which generally occurred after 6 centrifugations, each of which involved a contact time of about ½ min.

Interhalogen Compounds.—Polonium dichloride with iodine in carbon tetrachloride gives a black solid which was shown by X-ray powder photography to contain polonium tetraiodide, presumably formed by the disproportionation of an intermediate interhalogen compound. Polonium dibromide, under similar conditions, gives a black solid which may be polonium dibromodiiodide; the X-ray powder photographs indicated the presence of a new compound of low symmetry.

X-Ray Crystallography.—In previous work [3] crystallography of polonium compounds was complicated by the poor quality of the X-ray diffraction photographs. The same trouble has been experienced in the present work, and in general the diffraction photographs of the polonium–iodine compounds were of poorer quality than those of the chlorides and bromides.

Polonium tetraiodide. The diffraction pattern could not be indexed, owing to the apparent low symmetry of this compound and the poor quality of the photographs. The $\sin^2\theta$ values and the observed intensities are given below for identification.

$\sin^2\theta$ ...	0·0142	0·0387	0·0444	0·0600	0·0641	0·0810	0·1022	0·1106	0·1223	0·1331
I_s	vw	w	w+	w−	m−	vw	vvw	vw	vvw	vvw

Cæsium hexaiodopolonite and hexaiodotellurite. The diffraction pattern of cæsium hexaiodopolonite was indexed on the basis of a face-centred cubic cell with $a = 5{\cdot}89 \pm 0{\cdot}01$ kX. This cell is too small to contain even one molecule of Cs_2PoI_6. The true unit cell edge is therefore probably $a = 11{\cdot}77 \pm 0{\cdot}05$ kX. With 4 molecules of Cs_2PoI_6 in this larger unit cell, the calculated density is 5·00 g./c.c. The cæsium, polonium, and iodine atoms were placed in the special

positions 8(c), 4(a), and 24(e) respectively of the space group O^5_h–Fm3m. The variable parameter for the iodine atoms was found from the intensity calculations to be $x = 0{\cdot}24$. This would give a Po–I distance of 2·82 kX. The agreement between the observed (I_o) and calculated (I_c) intensities is seen from Table 1 to be fair. The intensity calculations show that the diffraction lines due to the true cell have low structure factors and thus are not observed since the films all had high backgrounds due to the γ-radiation from the sample.

TABLE 1.

hkl	$\sin^2\theta_o$	$\sin^2\theta_c$	I_o	I_c *	*hkl*	$\sin^2\theta_o$	$\sin^2\theta_c$	I_o	I_c *	*hkl*	$\sin^2\theta_o$	$\sin^2\theta_c$	I_o	I_c *
111	—	0·0128	—	29·1	420	—	0·0854	—	7·4	600 } 442 }	—	0·1537	—	4·3
200	—	0·0171	—	10·9	422	—	0·1025	—	7·3					
220	—	0·0342	—	15·6	511 } 333 }	—	0·1153	—	12·7	620	—	0·1708	—	4·1
311	—	0·0470	—	15·4						533	—	0·1836	—	2·4
222	0·512	0·0512	w	86·5	440	0·1366	0·1366	w	69·5	622	0·1874	0·1879	vw	36·6
400	0·683	0·0683	w+	100·0	531	—	0·1495	—	11·4	444	0·2047	0·2050	vw	26·1
331	—	0·0811	—	3·3										

* $I_c \propto F^2p(1 + \cos^2 2\theta)/\sin^2\theta\cos\theta$.

From the earlier studies it was found that the complex compounds M_2PoX_6 (M = Cs or NH_4, X = Cl or Br) were isostructural with their tellurium analogues. The compound Cs_2TeI_6 should therefore be isostructural with Cs_2PoI_6. As the tellurium compound presents no handling difficulties, the diffraction photographs were obtained by using the Guinier-type camera.[3] The weak lines due to the true unit cell of Cs_2TeI_6 were thus readily observed. The structure is face-centred cubic, with $a = 11{\cdot}698 \pm 0{\cdot}005$ kX, and the compound is isostructural with its polonium analogue. With 4 molecules per unit cell the calculated density is 4·76 g./c.c. The cæsium, tellurium, and iodine atoms were placed on the 8(c), 4(a), and 24(e) special positions respectively of the space group O^5_h–Fm3m. The weakness of the diffraction lines due to the

TABLE 2.

hkl	$\sin^2\theta_o$	$\sin^2\theta_c$	I_o	I_c *	*hkl*	$\sin^2\theta_o$	$\sin^2\theta_c$	I_o	I_c *	*hkl*	$\sin^2\theta_o$	$\sin^2\theta_c$	I_o	I_c *
111	0·0130	0·0130	vw	6·9	420	0·0865	0·0865	vvw	2·6	600 } 442 }	0·1562	0·1557	vvw	1·4
200	0·0173	0·0173	vvw	3·5	422	0·1039	0·1038	vvw	2·5					
220	0·0347	0·0346	vw⁻	5·6	511 } 333 }	0·1171	0·1168	vvw	2·7	620	—	0·1730	—	1·2
311	0·0475	0·0476	vw	5·8						533	—	0·1860	—	0·9
222	0·0518	0·0519	s	100	440	0·1385	0·1384	m	59·4	622	0·1903	0·1903	m—	45·7
400	0·0692	0·0692	m+	83·4	531	0·1514	0·1514	vvw	2·8	444	0·2076	0·2076	w+	21·3
331	0·0821	0·0822	vvw	2·4										

* See Table 1.

true cell made it difficult to determine the variable parameter for the iodine atom in both the polonium and the tellurium compound; the value found from the intensity calculations was 0·248 which gave a Te–I distance of 2·90 kX. Agreement between the observed and the calculated values of $\sin^2\theta$ and the observed (I_o) and calculated (I_c) intensities is seen to be good (Table 2).

The Octahedral Covalent Radius of Polonium.—Pauling has derived the octahedral covalent radius of tin (46 silver core $5s^25p^2$) and lead (78 gold core $6s^26p^2$) from the experimentally determined interatomic distances in the complex ions $[SnCl_6]^{2-}$ and $[PbBr_6]^{2-}$ respectively. These radii, which are about 3% greater than their corresponding tetrahedral (sp^3) radii, correspond to sp^3d^2 bonds and not to d^2sp^3 bonds. However, the octahedral radius of selenium (28 copper core $4s^24p^4$) was found to be 23% greater than its tetrahedral radius. There is in Se^{IV}, in the ion $[SeBr_6]^{2-}$, an unshared pair of electrons which occupy the 4*s* orbital, and this orbital is therefore not available for use in forming sp^3d^2-type bonds. Pauling [4] suggests that it is the 5*s* orbital which is used for bond formation, the bonds being $4p^34d^25s$ bonds, and that the use of the 5*s* orbital explains why the octahedral radius is greater than the tetrahedral.

[3] D'Eye, British report A.E.R.E. C/R 1524, 1954, SO-70-674-1-78.
[4] Pauling, "The Nature of the Chemical Bond," Cornell Univ. Press, Ithaca, New York, 2nd Edn., 1944.

A recent *X*-ray structural investigation [5] of the compound $(NH_4)_2SbCl_5$ shows that in the $[SbCl_5]^{2-}$ ion, the antimony is at the centre of an octahedron of which five corners are occupied by chlorine with the unshared electron pair of the antimony directed towards the sixth corner. From the stereochemical aspect an unshared pair in an ion of this type is not an " inert " pair. In the $[SeBr_6]^{2-}$ ion, the 4*s* pair must be truly inert since the 5*s* orbital has replaced the 4*s* orbital with respect to bond formation and the configuration, but not the size, of the complex is the same as it would be if the inert pair were not present.

Tellurium (46 silver core $5s^25p^4$) and polonium (78 gold core $6s^26p^4$) have the same outer-electron configuration as selenium and it might therefore be expected that their octahedral radii would be greater than their tetrahedral radii and that the orbitals used in bond formation would be $5p^35d^26s$ and $6p^36d^27s$ respectively. The octahedral radius of tellurium is, in fact, 17% greater than the tetrahedral radius. Our value for the octahedral radius of Te^{IV}, in the $[TeBr_6]^{2-}$ ion, agrees with the value of 1·52 kX quoted by Pauling,[4] but the value obtained from the $[TeI_6]^{2-}$ ion is 1·62 kX. It is probable that this high value results from the difficulty in determining the variable parameter for the iodine atom, since the diffraction lines attributed to the true cell have small structure factors.

The values of the octahedral covalent radius of Po^{IV}, obtained from the different complex compounds, are given in Table 3. These values can only be approximate since

TABLE 3.

Compound	Po–halogen distance (kX)	Po^{IV} radius (kX)	Ref.
$(NH_4)_2PoCl_6$	2·38	1·39	2
Cs_2PoCl_6	2·54	1·55	6
$(NH_4)_2PoBr_6$	2·60	1·49	2
Cs_2PoBr_6	2·64	1·53	2
Cs_2PoI_6	2·82	1·54	—

the unit-cell dimensions for these compounds were determined from low-angle diffraction lines : high-angle diffraction lines were not available owing to the rather poor diffraction photographs.[2] The tetrahedral radius of polonium has not been determined experimentally, but a value of 1·46 kX has been obtained by extrapolation from the tetrahedral radii of silver, mercury, thallium, lead, and bismuth. The octahedral radius of Po^{IV}, if taken to be about 1·52 kX, is about 4% greater than the tetrahedral radius : this small difference would be expected from the progressive decrease observed from selenium to tellurium.

The authors thank Miss G. Booth for assistance in measuring the *X*-ray films and in the computation.

UNITED KINGDOM ATOMIC ENERGY AUTHORITY,
HARWELL, NR. DIDCOT, BERKS.

[*Received, March 26th*, 1956.]

[5] Edstrand, *Svensk Kem. Tidskr.*, 1955, **67**, 230.
[6] Staritzky, American Report LA-1286, 1951.

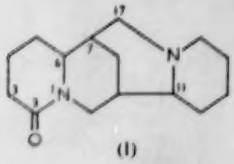
658. *The Lupin Alkaloids. Part XVI.* The Synthesis of Externally Compensated Lupanine.*

By G. R. Clemo, R. Raper, and J. C. Seaton.

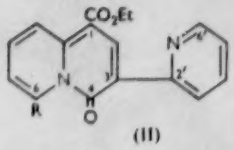
2 : 3-Dehydro-2-methylsparteine (VII) has been synthesised from 1-ethoxycarbonyl-6-methyl-4-oxo-3-2′-pyridylpyridocoline [1] (II; R = Me). The former, prepared from (±)-lupanine by a variation of Winterfeld's method,[2] has been used as a relay in the total synthesis of the alkaloid itself.

Of the major lupin alkaloids, lupanine, lupinine, and sparteine, the last two have already been synthesised.[3] Structure (I) was ascribed to the first of these alkaloids by two of us [4] and it is probable [5] that in it the hydrogen atom at position 6 is *cis*, and that at position 11 *trans*, with respect to the methylene bridge between positions 7 and 9.

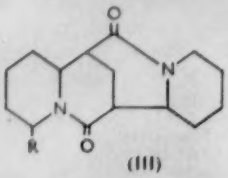
We have now synthesised this alkaloid by the following method. 1-Ethoxycarbonyl-4-oxo-3-2′-pyridylpyridocoline-6-carboxylic acid (II; R = CO_2H), prepared by heating 1-ethoxycarbonyl-6-methyl-4-oxo-3-2′-pyridylpyridocoline [1] (II; R = Me) to its melting point with selenium dioxide, was esterified by treating it successively with thionyl chloride



(I)



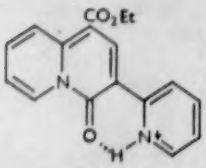
(II)



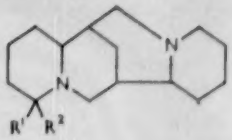
(III)

and ethanol, and the resulting diethyl ester was freed from selenium by refluxing in ethanol solution over stirred mercury.[6] This starting material was chosen rather than the isomeric 6′-methyl compound because, when Galinowsky and Kainz [7] hydrogenated 1-ethoxycarbonyl-4-oxo-3-2′-pyridylpyridocoline over platinum in ethanolic hydrogen chloride and cyclised the product, only the dioxosparteine (III; R = H) with the *cis-trans*-configuration was obtained. This is explicable if hydrogenation takes place from one side only of the molecules which is hydrogen-bonded (IV).

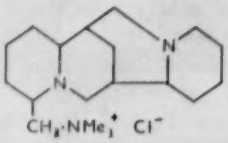
We therefore expected that when the diester (II; R = CO_2Et) was hydrogenated under



(IV)



(V)



(VI)

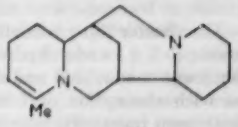
similar conditions and then cyclised, the *cis-trans*-isomers would predominate in the product. The viscous gum so obtained was washed in chloroform solution with dilute hydrochloric acid to remove basic unsaturated and uncyclised materials, after which distillation gave a product which partially crystallised, and was separated by chromatography on alumina

* Part XV, *J.*, 1954, 2693.

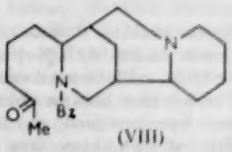
[1] Clemo, Fox, and Raper, *J.*, 1954, 2693.
[2] Winterfeld and Hoffmann, *Arch. Pharm.*, 1937, **275**, 5.
[3] Clemo, Morgan, and Raper, *J.*, 1938, 1574; Clemo, Raper, and Short, *J.*, 1949, 663.
[4] Clemo and Raper, *J.*, 1933, 644.
[5] Leonard and Beyler, *J. Amer. Chem. Soc.*, 1950, **72**, 1316; Marion and Leonard, *Canad. J. Chem.*, 1951, **29**, 355; Marion, *Bull. Soc. chim. France*, 1954, 1189.
[6] Jacques, *ibid.*, 1955, 1293.
[7] Galinovsky and Kainz, *Monatsh.*, 1947, **77**, 137.

into four crystalline 2-ethoxycarbonyl-10 : 17-dioxosparteines (III; R = CO_2Et), two of which appeared to predominate in the mixture.

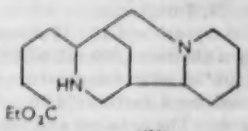
This separation was, however, very tedious, and, since the number of diastereoisomers is halved at later stages of the synthesis, we reduced the unseparated mixture by means of lithium aluminium hydride, obtaining a mixture of 2-hydroxymethylsparteines (V; $R^1 = H$, $R^2 = CH_2{\cdot}OH$) which did not crystallise. Chlorination of this with thionyl chloride gave a product which again could not be crystallised and which decomposed on attempted distillation, possibly because of quaternisation, since water-soluble materials were formed. The crude product was therefore condensed with trimethylamine, giving an ether-insoluble highly deliquescent solid (VI). Hofmann degradation of this would be expected to yield a mixture containing (V; $R^1R^2 = CH_2$:). Acid would convert this into a 1 : 2-dehydro-2-methyl-1-sparteinium salt, which on basification would give 2 : 3-dehydro-



(VII)



(VIII)



(IX)

2-methylsparteine (VII) through a *pseudo*-base. Treating the chloride (VI) in this way we obtained an unsaturated gum, which, on fractionation on alumina, gave the base (VII) as an unstable oil, characterised as its mono- and di-picrate and dihydriodide, all of which were crystalline.

Winterfeld *et al.*[2] prepared this base by the action of methylmagnesium iodide on lupanine, and described it as an oil unstable even in the absence of air. Using slightly different conditions we obtained it from lupanine in improved yield as a colourless solid, m. p. 34°, whose mono- and di-picrate and dihydriodide were identical with those obtained from our synthetic material. Although our platinichloride had a different decomposition point from that recorded by Winterfeld *et al.*, the dihydrobromide and dihydro-derivative have physical constants agreeing with those recorded by him. The failure of our synthetic material to crystallise is probably to be ascribed to the presence in it of diastereoisomers.

This base was then used as a relay. With benzoyl chloride in aqueous alkaline solution it yielded the ketone (VIII) as a stiff gum, which was purified through its crystalline monopicrate. It gave the iodoform reaction and a crystalline 2 : 4-dinitrophenylhydrazone hydrochloride. Analogous compounds have been prepared.[2,8] The ketone (VIII) was shaken with sodium hypobromite in dioxan, and the amino-acid resulting was simultaneously esterified and debenzoylated by ethanolic hydrogen chloride. The product, when heated, gave colourless prismatic plates identical with (±)-lupanine obtained from the seeds of *Lupinus termis*. The picrate and thiocyanate were also identical. A trace of another substance richer in oxygen was also obtained, which may be an externally compensated hydroxylupanine.

The ester (IX) obtained by hydrolysis of lupanine (cf. Winterfeld *et al.*[9]) cyclised spontaneously to lupanine. We find, however, that the decomposition point of the platinichloride of this ester differs from that recorded by him, and we have obtained in addition a crystalline dihydrochloride.

Experimental

1-Ethoxycarbonyl-4-oxo-3-2′-pyridylpyridocoline-6-carboxylic Acid (II; R = CO_2H).—A finely ground mixture of 1-ethoxycarbonyl-6-methyl-4-oxo-3-2′-pyridylpyridocoline (II; R = Me) (10 g.) and freshly sublimed selenium dioxide (8 g.) was stirred and heated to 150°; the mass melted. After cooling to 130° during 3—4 min. a vigorous reaction took place with evolution of steam. The temperature was raised to 150° for 15 min., whereupon the melt solidified. The cooled mass was dissolved in hot hydrochloric acid, and the solution filtered and cooled; the acid separated and recrystallised from water as its *hexahydrate* (9·4 g.), orange needles

[8] Winterfeld and Petkow, *Ber.*, 1949, **82**, 156; Petkow, *Scientia Pharmaceutica*, 1948, **16**, 57.
[9] Winterfeld, Hoffmann, and Holschneider, *Arch. Pharm.*, 1937, **275**, 65.

softening at 160—165°, m. p. 220° (decomp.) (Found : C, 48·55; H, 5·7. $C_{15}H_{14}O_5N_2.6H_2O$ requires C, 48·4; H, 5·8%). The *anhydrous acid* obtained by drying at 150°/1 mm. had m. p. 220° (decomp.) (Found : C, 64·0; H, 4·4; N, 8·2. $C_{15}H_{14}O_5N_2$ requires C, 63·9; H, 4·1; N, 8·3%).

1 : 6-*Diethoxycarbonyl*-4-*oxo*-3-2′-*pyridylpyridocoline* (II; R = CO_2Et).—The anhydrous acid (30 g.) and thionyl chloride (250 ml.) were refluxed for 1 hr., the excess of thionyl chloride was removed under reduced pressure, benzene (20 ml.) added, and the whole again evaporated. Ethanol (250 ml.) was added to the cooled residue and the whole refluxed for 1 hr. The excess of ethanol was removed and the diester liberated with potassium carbonate and extracted with chloroform. The extract was dried (Na_2SO_4) and evaporated, leaving the *diester*, which solidified and was recrystallised from light petroleum (b. p. 100—120°) or ethanol. Its ethanol solution was refluxed overnight over stirred mercury, and when filtered and cooled deposited pale yellow needles (12·5 g.), m. p. 141° (Found : C, 65·75; H, 5·15; N, 7·6. $C_{20}H_{18}O_5N_2$ requires C, 65·6; H, 4·9; N, 7·6%).

2-*Ethoxycarbonyl*-10 : 17-*dioxosparteine* (III; R = CO_2Et).—The diester (30 g.) in ethanolic hydrogen chloride (200 ml. of 2%) was shaken with platinum oxide (0·5 g.) under hydrogen at 105 lb./in.² at room temperature for 48 hr. Platinum oxide (0·5 g.) was then added and shaking continued for a further 72 hr. The solution became colourless with absorption of 7 mols. of hydrogen. The catalyst and solvent were removed, and the thick gum remaining was basified with potassium carbonate and extracted with chloroform. The solvent was removed from the dried extract, and the residual gum heated for 2 hr. at 200°/8 mm., the liquid becoming quiescent. A chloroform solution of the cooled material was washed with dilute hydrochloric acid, and removal of the solvent from the dried solution left a mixture of stereoisomeric 2-ethoxycarbonyl-10 : 17-dioxosparteines (19 g.) which distilled at 210—224°/0·2 mm. (Found : C, 65·1; H, 8·0. Calc. for $C_{18}H_{26}O_4N_2$: C, 64·7; H, 7·8%). When kept it partly solidified. The distillate (3·5 g.) was adsorbed from light petroleum (b. p. 60—80°) on a column of alumina (100 g.). Elution with light petroleum–benzene (1 : 1) gave a pale gum which partly solidified and was recrystallised from ether, yielding a *stereoisomer* as large colourless prismatic needles (0·6 g.), m. p. 146—147° (Found : C, 64·7; H, 7·9; N, 8·6. $C_{18}H_{26}O_4N_2$ requires N, 8·4%). Benzene–chloroform (9 : 1) then eluted a different *form* as a gum, which crystallised from its ethereal solution in large, colourless, hexagonal prisms (0·6 g.), m. p. 146° (Found : C, 64·7; H, 7·6; N, 8·5%). Concentration of the mother-liquor gave colourless rhombs (0·05 g.) of a third *form*, m. p. 138° (Found : C, 64·5; H, 8·5%). Finally chloroform eluted a gum, the ethereal solution of which deposited a fourth *form* as large prismatic needles (0·07 g.), m. p. 172° (Found : C, 64·5; H, 8·5%). Each of these four substances depressed the m. p.'s of the other three, all were soluble in water, and none formed a picrate.

2-*Hydroxymethylsparteine* (V; R^1 = H, R^2 = CH_2·OH).—The mixture of isomeric ethoxycarbonyldioxosparteines (12 g.) in dry ether (240 ml.) was added slowly with stirring to a refluxing solution of lithium aluminium hydride in ether (240 ml. of 80-vol.). A yellow precipitate was formed and the mixture was refluxed for 6 hr. and left overnight. The excess of lithium aluminium hydride was decomposed with water, and concentrated sodium hydroxide solution was added. The resulting paste was extracted several times with ether, the extract dried (Na_2SO_4), and the solvent removed, leaving the *alcohol* which distilled as a pale yellow oil (4·5 g.), b. p. 135—140°/0·2 mm. (Found : C, 72·6; H, 10·9. $C_{16}H_{28}ON_2$ requires C, 72·7; H, 10·6%). The *dipicrate*, from ethanol, was yellow and microcrystalline, m. p. 110—116° (Found : C, 46·7; H, 5·0. $C_{16}H_{28}ON_2.2C_6H_3O_7N_3$ requires C, 46·5; H, 4·7%).

2 : 3-*Dehydro*-2-*methylsparteine* (VII).—(*a*) A solution of the above alcohol (6 g.) in ether (300 ml.) was cooled and stirred while thionyl chloride (24 ml.) was added slowly. A precipitate was formed and the mixture was refluxed for 2 hr., after which the solvent and excess of thionyl chloride were removed under reduced pressure. The residue was cooled, basified with potassium carbonate solution, and extracted with ether. The extract was dried (Na_2SO_4) and the solvent removed, leaving a pale oil (6 g.) which decomposed when heated and did not give a crystalline picrate or picrolonate. This oil (6 g.) was heated with trimethylamine (12 g.) in ethanol (50 ml.) at 100° for 7 hr. Removal of the solvent left a thick, light red gum which solidified when it was extracted several times with boiling ether. This solid was very deliquescent and gave a positive test for ionic chlorine. A solution of it (3 g.) in water (20 ml.) was shaken with excess of freshly prepared silver oxide for 1 hr., the solids were filtered off, and the filtrate was evaporated in a vacuum below 45°. The residue was heated to 200°/0·2 mm., the distillate being collected in a trap cooled in liquid air and dissolved in dilute hydrochloric acid. After basification with potassium carbonate and extraction with ether the extract was dried (Na_2SO_4), the ether was

removed, and the residue distilled as a pale yellow oil (0·4 g.), b. p. 100—150°/0·2 mm. The ether distillate with picric acid gave trimethylamine picrate (0·4 g.), m. p. and mixed m. p. 219°. The oil was adsorbed from light petroleum (b. p. 60—80°) on alumina [12 g., Savory and Moore, "For chromatographic analysis," deactivated with water (0·4 g.)] and eluted with successive 10 ml. quantities of the same solvent. Fractions 4—10, when united and evaporated, left a colourless oily *base* (0·1 g.), b. p. 130—140° (bath-temp.)/0·2 mm. (Found: C, 77·8; H, 10·9. $C_{16}H_{24}N_2$ requires C, 78·0; H, 10·6%. Winterfeld *et al.* give no analysis of this compound). The *monopicrate* crystallised from ethanol in orange needles, m. p. 148° (Found: C, 55·2; H, 6·15. $C_{16}H_{24}N_2,C_6H_3O_7N_3$ requires C, 55·6; H, 6·1%). The *dipicrate* crystallised from ethanol in yellow diamond-shaped prisms, m. p. 199—200° (Found: C, 47·55; H, 4·55. $C_{16}H_{24}N_2,2C_6H_3O_7N_3$ requires C, 47·7; H, 4·5%). The *dihydriodide* formed large prisms (from ethanol), m. p. 254° (Found: C, 38·35; H, 5·8. $C_{16}H_{24}N_2,2HI$ requires C, 38·2; H, 5·6%). The m. p.s of these derivatives were not depressed on admixture with specimens prepared from the base obtained as described below. Further elution of the alumina column gave oils which neither crystallised nor gave crystalline derivatives.

(*b*) A solution of (±)-lupanine, m. p. 99° (10 g.), in ether (150 ml.) was added with stirring to a boiling Grignard reagent prepared from magnesium (3·5 g.), methyl iodide (17·4 g.), and ether (200 ml.). The mixture was stirred and refluxed for a further 3 hr. and then kept overnight. The excess of Grignard reagent was decomposed with water, and the solid complex with hydrochloric acid. The base was liberated with aqueous sodium hydroxide and extracted with ether, the extract dried (Na_2SO_4), the solvent removed, and the residue distilled, yielding a colourless oil (8·5 g.), b. p. 130°/0·2 mm., which soon solidified and had then m. p. 34° (Found: C, 78·4; H, 10·7; N, 11·3. $C_{16}H_{24}N_2$ requires N, 11·4%). The solid was easily soluble in the commoner organic solvents, and on exposure to air it resinified. The platinichloride crystallised from dilute hydrochloric acid in orange prisms, decomp. 265° (Winterfeld *et al.* give 245—250°) (Found: C, 28·9; H, 4·6; Pt, 30·0. Calc. for $C_{16}H_{26}N_2,H_2PtCl_6$: C, 29·3; H, 4·5; Pt, 29·75%). The monopicrate crystallised in orange needles, m. p. 148° (Found: C, 55·4; H, 5·8%), the dipicrate in yellow prisms, m. p. 199—200° (Found: C, 47·8; H, 4·7%), and the dihydriodide in large colourless prisms, m. p. 254° (Found: C, 38·2; H, 5·9; N, 5·5%. Calc. for $C_{16}H_{24}N_2,2HI$: C, 38·2; H, 5·6; N, 5·6%). The dihydrobromide formed colourless prisms, m. p. 180°, from ethanol (Winterfeld *et al.* give 180°) (Found: N, 6·3. Calc. for $C_{16}H_{24}N_2,2HBr,H_2O$: N, 6·4%). 2-Methylsparteine, obtained from this base by hydrogenation, crystallised from light petroleum (b. p. 40—60°) in prismatic plates, m. p. 48—50° (Winterfeld *et al.*, 48—50°) (Found: C, 77·5; H, 11·35; N, 11·0. Calc. for $C_{16}H_{28}N_2$: C, 77·4; H, 11·3; N, 11·3%), and gave a monopicrate, m. p. 152° (Winterfeld *et al.*, 221° for hydrated material) (Found: C, 55·3; H, 6·3. Calc. for $C_{16}H_{28}N_2,C_6H_3O_7N_3$: C, 55·35; H, 6·5%), and a *dipicrate*, m. p. 213° (Found: C, 47·8; H, 5·1. $C_{16}H_{28}N_2,2C_6H_3O_7N_3$ requires C, 47·6; H, 4·8%).

3-Benzoyltetrahydrodeoxy-4-4'-oxopentylcytisine (VIII).—A mixture of 2:3-dehydro-2-methylsparteine (50 g.) and water (200 ml.) was kept alkaline with sodium hydroxide (8%) while benzoyl chloride (50 ml.) was added in small quantities during 1 hr. with continuous shaking. After a further 2 hours' shaking the thick yellow oil was extracted with ether, the extract dried (KOH), and the solvent removed. The residue was distilled and the fraction of b. p. 250°/0·2 mm. collected as a very viscous pale yellow oil which did not crystallise but gave a *picrate*; this, recrystallised three times from ethanol, formed large yellow rhombic prisms (26 g.), m. p. 136° (Found: C, 58·5; H, 6·1. $C_{22}H_{32}O_2N_2,C_6H_3O_7N_3$ requires C, 58·3; H, 5·9%). The picrate was decomposed with hydrochloric acid, the mixture basified with sodium hydroxide, and the base extracted with ether. The extract was dried (Na_2SO_4) and the solvent removed after which the residue distilled with slight decomposition, giving a pale yellow viscous oil (15 g.), b. p. 250°/0·2 mm. The 2:*4-dinitrophenylhydrazone hydrochloride* crystallised from water in yellow hydrated prisms, m. p. 145° (Found: C, 56·2; H, 7·1. $C_{29}H_{34}O_5N_6,HCl,2H_2O$ requires C, 56·1; H, 6·6%). Dehydration at 120°/0·2 mm. for 2 hr. gave the *anhydrous derivative* as a dark orange, viscous oil (Found: C, 59·0; H, 6·4. $C_{29}H_{34}O_5N_6,HCl$ requires C, 59·5; H, 6·3%).

(±)-*Lupanine* (I).—A solution of the above ketone (15 g.) in dioxan (300 ml.) was cooled while a solution of sodium hypobromite [from bromine (20 g.), sodium hydroxide (17·5 g.), and water (350 ml.)] was added. After being shaken for 15 min. the mixture was evaporated, the residue dissolved in water (100 ml.), and the solution extracted with ether. The aqueous layer was acidified with hydrochloric acid and evaporated to dryness. After absolute ethanol (50 ml.) had been added and the whole again evaporated the residue was extracted thrice with boiling absolute ethanol (100 ml.). The combined extracts were saturated with dry hydrogen chloride,

set aside overnight, then refluxed for 6 hr. The solution was evaporated to dryness, the residue basified with potassium carbonate solution, and the liberated base extracted with ether. The extract was dried (Na_2SO_4), the solvent removed, and the residue heated at 200°/8 mm. for 1 hr. Distillation gave a colourless oil (2·5 g.), b. p. 160—180°/2 mm., a solution of which in light petroleum (b. p. 60—80°) deposited colourless needles (0·1 g.) of a (?)*hydroxylupanine*, m. p. 154° (Found: C, 67·8; H, 9·35. $C_{15}H_{24}O_2N_2$ requires C, 68·2; H, 9·1%). The *picrate* crystallised from ethanol–ether in yellow prisms, m. p. 244°. Concentration of the light petroleum mother-liquors gave (+)-lupanine which crystallised in prismatic plates (1·7 g.), m. p. 99° (Found: C, 72·4; H, 10·0. Calc. for $C_{15}H_{24}ON_2$: C, 72·6; H, 9·7%). The picrate crystallised from ethanol in yellow prisms, m. p. 229° (Found: C, 53·0; H, 5·7. Calc. for $C_{15}H_{24}ON_2,C_6H_3O_7N_3$: C, 52·8; H, 5·7%). The thiocyanate crystallised from water in colourless hydrated prisms, m. p. 124° (Found: C, 59·1; H, 8·5. Calc. for $C_{15}H_{24}ON_2,HCNS,H_2O$: C, 59·1; H, 8·3%). The m. p.s. of the base and these salts were not depressed by admixture with authentic specimens.

Hydrolysis of (±)-*Lupanine with Hydrochloric Acid.*—(±)-Lupanine (5 g.) was hydrolysed, by Winterfeld's procedure, the ethyl ester of the amino-acid being isolated as its *dihydrochloride* which crystallised from ethanol in colourless needles (3·0 g.), m. p. 208° (decomp.) (Found: Cl, 19·25. $C_{17}H_{30}O_2N_2,2HCl$ requires Cl, 19·3%). The platinichloride crystallised from dilute hydrochloric acid–ethanol in orange plates, decomp. 230° (Winterfeld *et al.*, 245°) (Found: Pt, 26·9. Calc. for $C_{17}H_{30}O_2N_2,H_2PtCl_6,H_2O$: Pt, 26·9%). The ester cyclised when kept or distilled, giving (±)-lupanine, m. p. 99° not depressed on admixture with an authentic specimen.

One of us (J. C. S.) thanks the D.S.I.R. for a maintenance grant.

UNIVERSITY OF DURHAM, KING'S COLLEGE,
NEWCASTLE UPON TYNE, 1.

[*Received, May 7th*, 1956.]

---

659. *The Resolution of Secondary and Tertiary Alcohols containing the Pyridyl Group.*

By ALWYN G. DAVIES, J. KENYON, and KUMAR THAKER.

Phenyl-2-pyridylmethanol, phenyl-4-pyridylmethanol, and 1-phenyl-1-2′-pyridylpropanol have been resolved by crystallisation of their salts with (+)-tartaric acid. 1-Phenyl-1-4′-pyridylpropanol and 1-phenyl-1-2′-pyridylethanol did not give crystalline salts with optically active acids, but the latter alcohol was resolved *via* the brucine salt of its hydrogen phthalate.

ALTHOUGH the usual method of resolving alcohols is by recrystallisation of salts of their acid esters with optically active bases, it was decided to take advantage of the basic character of pyridylcarbinols and attempt their resolution by recrystallisation of their salts with optically active acids.

Phenyl-2-pyridylmethanol, prepared by the reduction of phenyl 2-pyridyl ketone with aluminium *iso*propoxide, gave a hydrogen (+)-tartrate which readily crystallised from ethanol. The solid yielded the (−)-alcohol which, after it had been twice recrystallised, was optically pure. The filtrate yielded the (+)-alcohol.

Phenyl-4-pyridylmethanol forms a crystalline hydrogen (+)-tartrate from ethanol. Two recrystallisations of the salt, followed by two crystallisations of the alcohols recovered from the crystals and the mother-liquor respectively, likewise yielded the optically pure (−)- and (+)-alcohol.

By the usual method both these secondary alcohols gave crystalline hydrogen phthalates, but attempts to prepare crystalline alkaloidal salts were unsuccessful. The hydrogen phthalates in 0·3N-sodium hydroxide did not disproportionate to the dialkyl phthalates, nor did they react with sodium toluene-*p*-sulphinate to form sulphones; instead they were hydrolysed to the alcohols.

The tertiary alcohols 1-phenyl-1-2′-pyridylpropanol, 1-phenyl-1-4′-pyridylpropanol, and 1-phenyl-1-2′-pyridylethanol were prepared by the Grignard reaction from the phenyl pyridyl ketone.

1-Phenyl-1-2′-pyridylpropanol gave a crystalline hydrogen (+)-tartrate from ethanol.

The less soluble fractions yielded the (+)-alcohol which was optically pure after one recrystallisation; the (−)-alcohol was obtained similarly from the more soluble hydrogen tartrate. 1-Phenyl-1-4′-pyridylpropanol, however, did not form a crystalline salt with (+)-tartaric acid, (+)-camphoric acid, or (+)-camphor-10-sulphonic acid and could not be resolved.

Attempts to prepare a crystalline hydrogen (+)-tartrate and (+)-camphorate of 1-phenyl-2′-pyridylethanol were unsuccessful. The hydrogen phthalate of the alcohol, however, yielded a crystalline brucine salt from acetone. After one recrystallisation from ethyl acetate this gave the (−)-hydrogen phthalate which was hydrolysed to the (+)-alcohol. The optically impure (+)-hydrogen phthalate was recovered from the more soluble fraction of the brucine salt.

Like the secondary alcohols and their hydrogen phthalates, 1-phenyl-1-2′-pyridylpropanol, and 1-phenyl-1-2′-pyridylethanol and its hydrogen phthalate show little tendency to undergo unimolecular alkyl–oxygen heterolysis.

Experimental

(±)-*Phenyl-2-pyridylmethanol.*—Phenyl 2-pyridyl ketone (8 g.; m. p. 43—45°; supplied by Messrs. Reilly Tar and Chemical Corporation, New York) was reduced by Tschitschibabin's method [1] with zinc dust in alkaline ethanol to phenyl-2-pyridylmethanol, plates (3·7 g., 47%) (from benzene–light petroleum), m. p. 78° (lit., 78°,[2] 82° [1]). A higher yield (73%) of the alcohol, m. p. and mixed m. p. 78°, was obtained when the ketone (40 g.) was reduced with aluminium *iso*propoxide in boiling propan-2-ol for 2 hr. (Found: C, 77·3; H, 6·2; N, 7·9. Calc. for $C_{12}H_{11}ON$: C, 77·8; H, 6·0; N, 7·6%).

(+)- *and* (−)-*Phenyl-2-pyridylmethanol.*—After 2 days at room temperature a solution prepared by dissolving the (±)-alcohol (18·5 g.) and (+)-tartaric acid (15·0 g.) in warm ethanol (50 c.c.) deposited needles of the *hydrogen tartrate* (19·6 g.), m. p. 89—90° (Found, by titration with 0·1N-sodium hydroxide: equiv., 334. $C_{12}H_{11}ON,C_4H_6O_6$ requires equiv., 335). Recrystallisation of the acid tartrate at this stage did not appreciably increase the rotatory power of the alcohol subsequently liberated.

The less soluble acid tartrate was decomposed with sodium carbonate solution. An ethereal extract yielded the partially active alcohol (9·7 g.), m. p. 73—74°, $[\alpha]_D^{18}$ −16·5° (*l*, 1; *c*, 5·14 in $CHCl_3$). Recrystallisation from ether–light petroleum (30 c.c.: 20 c.c.) gave large pale yellow plates (6·8 g.), m. p. 73°, $[\alpha]_D^{18}$ −1·3° (*l*, 1; *c*, 4·42 in $CHCl_3$). From the filtrate the optically pure (−)-alcohol (2·1 g.) was recovered, having m. p. 66°, $[\alpha]_{5463}^{18}$ −67·8°, $[\alpha]_{4993}^{18}$ −86·2°, $[\alpha]_{4469}^{18}$ −104·7° (*l*, 1; *c*, 4·682 in $CHCl_3$), $[\alpha]_D^{18}$ −3° (*l*, 1; *c*, 2·713 in EtOH), $[\alpha]_D^{18}$ −3·2° (*l*, 1; *c*, 3·2 in acetone).

The mother-liquor containing the more soluble acid tartrate was concentrated and decomposed with sodium carbonate solution, yielding the alcohol (7·8 g.), m. p. 73—74°, $[\alpha]_D^{18}$ +17·3° (*l*, 1; *c*, 5·44 in $CHCl_3$). On recrystallisation from ether–light petroleum the almost racemic alcohol separated (5·2 g.), having m. p. 78°, $[\alpha]_D^{18}$ +1·6° (*l*, 1; *c*, 4·55 in $CHCl_3$). The filtrate yielded the optically pure (+)-alcohol as plates (1·8 g.), m. p. 66°, $[\alpha]_D^{18}$ +84·8° (*l*, 1; *c*, 3·352 in $CHCl_3$).

(±)-*Phenyl-2-pyridylmethyl Hydrogen Phthalate.*—A mixture of the (±)-alcohol (3·7 g.), phthalic anhydride (2·96 g.), and pyridine (1·6 g.) was heated on a water-bath for 5 hr. Next day the mixture was diluted with iced water. The solid which separated was washed free from pyridine with water, dried (5·8 g.; m. p. 140—145°), and recrystallised from acetone, yielding the *hydrogen phthalate* as plates (3·9 g., 55%), m. p. 145—146° (Found: C, 72·0; H, 4·9; N, 4·5%; equiv., 334. $C_{20}H_{15}O_4N$ requires C, 72·1; H, 4·95; N, 4·2%; equiv., 333). Attempts to prepare a crystalline brucine salt of this acid ester were unsuccessful.

A solution of the hydrogen phthalate (0·5 g.) in 0·3N-sodium hydroxide (10 c.c.) next day had deposited the crystalline alcohol, m. p. and mixed m. p. 78°; no dialkyl phthalate could be isolated.

Solutions of the hydrogen phthalate (0·66 g.) in 0·3N-sodium hydroxide (10 c.c.) and of sodium toluene-*p*-sulphinate (0·43 g.) in water, were mixed. The alcohol gradually separated (m. p. and mixed m. p. 78°). No sulphone was formed.

[1] Tschitschibabin, *Ber.*, 1904, **37**, 1370.
[2] Ashworth, Daffern, and Hammick, *J.*, 1939, 809.

(±)-*Phenyl-4-pyridylmethanol.*—Phenyl 4-pyridyl ketone (m. p. 71—72°; supplied by Messrs. Reilly Tar and Chemical Corporation, New York) was reduced with zinc dust and alkaline ethanol by Tschitschibabin's method,[1] yielding crude phenyl-4-pyridylmethanol (63%). Two recrystallisations from benzene–light petroleum gave the pure alcohol as light yellow plates (32%), m. p. 120—121° (lit.,[1] m. p. 126°).

A higher yield (70%) of the alcohol, m. p. and mixed m. p. 120—121°, was obtained when the ketone (20 g.) was reduced with aluminium *iso*propoxide in boiling propan-2-ol for 1·5 hr. (Found: C, 77·5; H, 6·2; N, 7·65. Calc. for $C_{12}H_{11}ON$: C, 77·8; H, 6·0; N, 7·6%).

(+)- *and* (−)-*Phenyl-4-pyridylmethanol.*—After 2 days at room temperature, a solution prepared by dissolving the (±)-alcohol (18·5 g.) and (+)-tartaric acid (15 g.) in warm ethanol (50 c.c.) deposited the *hydrogen tartrate* (26·1 g.). Two recrystallisations gave the salt (18·4 g.) with m. p. 98—100° (Found: equiv., 334. $C_{12}H_{11}ON,C_4H_6O_6$ requires equiv., 335).

This least soluble salt was decomposed as described above, yielding the alcohol (9·5 g.), m. p. 123—124°, $[\alpha]_D^{18}$ −8·8° (*l*, 1; *c*, 2·44 in $CHCl_3$). Two recrystallisations from ethanol gave the optically pure (−)-*alcohol*, m. p. 131—132°, $[\alpha]_D^{18}$ −55·5° (*l*, 1; *c*, 3·656 in $CHCl_3$) (Found: C, 78·0; H, 5·97; N, 7·55%).

The first filtrate containing the more soluble hydrogen tartrate yielded the partially active alcohol (2·6 g.), m. p. 123—124°, $[\alpha]_D^{18}$ +11·2°. Two recrystallisations from ethanol gave the (+)-alcohol, m. p. 131—132°, $[\alpha]_D^{18}$ +52·4° (*l*, 1; *c*, 2·083 in $CHCl_3$).

(±)-*Phenyl-4-pyridylmethyl Hydrogen Phthalate.*—By the method described above, the alcohol (1·85 g.) yielded the *hydrogen phthalate* (2·2 g.), m. p. 190—192°, which was insoluble in most of the common organic solvents. It recrystallised from dioxan in plates, m. p. 195° (Found: equiv., 332. $C_{12}H_{15}O_4N$ requires equiv., 334). It did not give a crystalline brucine salt from acetone.

As with the isomeric 2-pyridyl compounds, attempts to prepare the dialkyl phthalate and *p*-tolyl sulphone resulted in the isolation of the alcohol.

(±)-1-*Phenyl-2-2′-pyridylpropanol.*—A solution of phenyl 2-pyridyl ketone (92 g.) in ether was added dropwise to an ethereal solution of ethylmagnesium bromide (from magnesium, 12 g., and ethyl bromide). Next day the mixture was decomposed with ice and ammonium chloride, and the product was recrystallised from ethanol, yielding 1-*phenyl-1-2′-pyridylpropanol* (45 g., 39%) as massive rhombs, m. p. 80—81° (Found: C, 79·0; H, 7·1; N, 6·6. $C_{14}H_{15}ON$ requires C, 78·8; H, 7·1; N, 6·6%). The alcohol gave a *picrate*, m. p. 105—106° (from ethanol) (Found: C, 74·7; H, 4·6; N, 12·2. $C_{20}H_{18}O_8N_4$ requires C, 74·3; H, 4·1; N, 12·6%).

(±)- *and* (−)-1-*Phenyl-1-2′-pyridylpropanol.*—After 2 days at room temperature a solution prepared by dissolving the (±)-alcohol (40 g.) and (+)-tartaric acid (28·1 g.) in warm ethanol (100 c.c.) deposited solvated crystals of the *hydrogen tartrate* (33·0 g.), m. p. 114—115° (Found: equiv., 408; after vacuum-desiccation, 362. $C_{14}H_{15}ON,C_4H_6O_6,C_2H_5OH$ requires equiv., 409. $C_{14}H_{15}ON,C_4H_6O_6$ requires equiv., 363).

The less soluble hydrogen tartrate (25 g.) was decomposed with aqueous sodium carbonate, liberating the partially active alcohol (14·2 g.), m. p. 71—72°, $[\alpha]_D^{22}$ +53·8° (*l*, 1; *c*, 3·941 in $CHCl_3$). This was dissolved in ethanol (100 c.c.) and the solution seeded with the (±)-alcohol. Next day the (±)-alcohol (3·1 g.) had separated; the filtrate yielded the optically pure (+)-alcohol, m. p. 68°, $[\alpha]_D^{22}$ +65·9° (*l*, 1; *c*, 4·52 in $CHCl_3$). These data were unchanged when the alcohol was recrystallised from ether–light petroleum.

The mother-liquors of the hydrogen tartrate were concentrated and decomposed, yielding the alcohol (21·8 g.), m. p. 73°, $[\alpha]_D^{22}$ −42·6° (*l*, 1; *c*, 5·216 in $CHCl_3$). This was dissolved in ethanol (80 c.c.) and seeded with the (±)-alcohol; next day the (±)-alcohol (7·8 g.) had separated. From the mother-liquor the (−)-*alcohol* was obtained (11·2 g.), m. p. 68°, $[\alpha]_D^{22}$ −66·2° (*l*, 1; *c*, 4·825 in $CHCl_3$) (Found: C, 79·0; H, 7·14; N, 6·47%).

Equal amounts (0·1 g.) of the (+)- and (−)-alcohol were dissolved in chloroform. Evaporation of the solvent left the (±)-alcohol, m. p. 78—80°.

The rotatory dispersion of the alcohol in various solvents is tabulated; the results lie on a typical " characteristic diagram " as devised by Armstrong and Walker.[2]

1-*Phenyl-1-2′-pyridylpropyl Hydrogen Phthalate.*—A mixture of the alcohol (1·065 g.), phthalic anhydride (0·74 g.), and trimethylamine (0·5 g.) was heated on the steam-bath for 6 hr. Next day the *hydrogen phthalate* was isolated in the usual way as crystals, m. p. 98—100° (from ether–light petroleum) (Found: equiv., 360. $C_{20}H_{21}O_4N$ requires equiv., 361).

After 2 days the alcohol was recovered from a solution of the alcohol (0·5 g.) and sodium toluene-*p*-sulphinate in formic acid (12 c.c.).

[2] Armstrong and Walker, *Proc. Roy. Soc.*, 1913, *A*, **88**, 388.

Specific rotatory power of 1-*phenyl*-1-2′-*pyridylpropanol* (*l*, 1; *t*, 18°).

Solvent	Wavelength (Å) 6563	5893	5463	4861	*c*
Pyridine	+13·1°	+15·1°	+18·7°	—	4·175
Dioxan	−2·6	−3·3	−4·1	−5·2°	5·102
99% EtOH	−6·5	−8·7	−10·4	—	2·20
$COMe_2$	−7·5	−10·7	−15·4	—	2·408
$MeNO_2$	−17·3	−23·3	−28·9	—	4·511
C_6H_6	−35·6	−45·6	−59·4	−62·4	1·568
$CHCl_3$	−52·6	−66·7	−84·6	−122·3	5·167
CS_2	−56·9	−72·6	−89·1	−101·8	2·29
AcOH	—	−85·3	—	—	2·048
2N-HCl	−83·0	−111·3	−135·5	−176·3	5·115

1-*Phenyl*-1-4′-*pyridylpropanol*.—Phenyl 4-pyridyl ketone is only sparingly soluble in ether. When it was added in ethereal suspension to ethereal ethylmagnesium bromide, the tertiary alcohol was obtained in only 12% yield. A better yield was obtained when the reactants were mixed in benzene solution as follows.

Ethyl bromide (27 g.) and magnesium (6 g.) were allowed to react in ether (150 c.c.); the solvent was then distilled off and the Grignard reagent dissolved in dry benzene (50 c.c.) and added dropwise to phenyl 4-pyridyl ketone (35 g.) in benzene (100 c.c.). The mixture was heated under reflux for 2 hr. Next day 1-*phenyl*-1-4′-*pyridylpropanol* was isolated in the usual manner and recrystallised from benzene–light petroleum as plates (38 g., 36%), m. p. 153—155° (Found: C, 78·9; H, 7·0; N, 6·6. $C_{14}H_{15}ON$ requires C, 78·8; H, 7·1; N, 6·6%).

(±)-1-*Phenyl*-1-2′-*pyridylethanol*.—The reaction between methylmagnesium iodide (magnesium, 5 g.) and phenyl 2-pyridyl ketone (38·6 g.) gave 1-phenyl-1-2′-pyridylethanol (30 g., 72%), b. p. 118°/0·2 mm., n_D^{20} 1·5812. After 1 month in the refrigerator the alcohol crystallised in large rhombs, m. p. 18—20°. Tilford, Shelton, and van Campen [4] report b. p. 115—120°/0·1 mm., n_D^{20} 1·5814.

(±)-*Phenyl*-1-2′-*pyridylethyl Hydrogen Phthalate*.—A mixture of the alcohol (21·3 g.), phthalic anhydride (14·8 g.), and triethylamine (10·5 g.) was heated on the steam-bath for 12 hr. Next day the mixture was added to sodium carbonate solution, then neutralised (phenolphthalein) with hydrochloric acid. An ethereal extract yielded the *hydrogen phthalate* (from ether–light petroleum; 17 g., 47%), m. p. 128—129° (decomp.) (Found: equiv., 359. $C_{20}H_{21}O_4N$ requires equiv., 361).

Brucine 1-*Phenyl*-1-2′-*pyridylethyl Phthalate*.—A solution of the hydrogen phthalate (42 g.) and brucine (47 g.) in acetone (200 c.c.) deposited the crystalline brucine salt, m. p. 146—150°, during 4 weeks at room temperature. One recrystallisation from ethyl acetate gave the salt (29·8 g.), m. p. 156—158°; the rotatory power of the derived hydrogen phthalate (see below) remained constant on further recrystallisation of this salt.

(+)- *and* (−)-1-*Phenyl*-1-2′-*pyridylethyl Hydrogen Phthalate*.—The least soluble fraction of the brucine salt was triturated with acetone (50 c.c.) and decomposed with 0·5N-sulphuric acid (76 c.c.). The insoluble brucine sulphate was filtered off, and the filtrate extracted with ether (50 c.c.; 2 × 25 c.c.). The dried ethereal extracts yielded the (−)-hydrogen phthalate as plates (11·8 g.), m. p. 136—138° (decomp.), $[\alpha]_D^{20}$ −8·6° (*l*, 1; *c*, 4·25 in $CHCl_3$).

The filtrate containing the more soluble brucine salt gave the optically impure (+)-hydrogen phthalate, $[\alpha]_D^{20}$ +2·2° (*l*, 1; *c*, 3·55 in $CHCl_3$).

(+)-1-*Phenyl*-1-2′-*pyridylethanol*.—The (−)-hydrogen phthalate (10 g.) was heated with 5N-sodium hydroxide (20 c.c.) on the steam-bath for 30 min. An ethereal extract yielded the (+)-alcohol (3·2 g.), b. p. 128°/0·8 mm., n_D^{20} 1·5813, $[\alpha]_D^{22}$ +38·2° (*l*, 1; *c*, 7·36 in $CHCl_3$), $[\alpha]_D^{20}$ +72·1° (*l*, 1; *c*, 3·328 in acetic acid), $[\alpha]_D^{20}$ +51·0° (*l*, 1; *c*, 1·47 in CS_2). When seeded at 0° with the (±)-alcohol, it crystallised, and had m. p. 16—18°.

The alcohol did not give a sulphone: nor did its hydrogen phthalate disproportionate.

Thanks are expressed to the Central Research Fund of the University for a Grant.

Chemistry Department, Battersea Polytechnic, London, S.W.11.
William Ramsay and Ralph Forster Laboratories,
University College, London, W.C.1. [*Received, May 22nd,* 1956.]

[4] Tilford, Shelton, and van Campen, *J. Amer. Chem. Soc.*, 1948, **70**, 4001.

660. *A Conductivity Method for the Accurate Determination of Carbon in Low-carbon Steels.*

By D. F. Dailly and T. A. Elliott.

A modified conductivity method for the determination of carbon in low-carbon steels (0·1%) with an accuracy of ±1% on samples of approx. 0·3 g. is described.

During the investigation of the decarburisation of steel by wet hydrogen, it became necessary to determine carbon concentrations in steels containing less than 0·1% of carbon to an accuracy of ±1% on quantities of metal which contained approximately 100 μg. of carbon. Standard methods, other than the low-pressure method, do not give the required accuracy, but Cain and Maxwell's conductivity method [1] provides the basis for a more accurate technique. They used a standard combustion train and absorbed the carbon dioxide by alkali, the change in resistance of which provided an estimate of the carbon.

Kalina and Joseph [2] described an absorber with a simple liquid circuit. The oxygen, carrying the carbon dioxide, was injected at the base of a vertical capillary tube causing the liquid to rise; the liquid returned by a tube from the top of the capillary to below the injection point. Ericsson [3] improved this system by employing a capillary tube (blown into bulbs for more efficient absorption) leading upwards to a chamber containing a dip-type conductivity cell, while the return circuit was a glass spiral of which the temperature was controlled by thermostat. More recent methods [4,5] have been directed towards compactness, secured by using a spiral absorption column, the production of a robust apparatus suitable for heavy usage, and greater accuracy.

General Considerations of Apparatus Design.—Size of sample. It was essential that the method should employ as small a sample (0·1—0·5 g.) as possible; the conditions chosen were those most suitable, evaporation losses and the time of determination being borne in mind, for the work in hand and permitting the use of a 0·3-g. sample. Each determination required approximately one hour.

Cell and absorption system. It seemed that the conventional low-frequency, high-frequency, or direct current method could be adopted; the high-frequency method has the advantage that the electrodes are not immersed in the alkali, but requires the screening of the thermostat bath. Use of direct current [6,7] permits simplification of the electrical circuit, but demands four immersed electrodes. For the low-frequency method, data [8-10] are available on work carried out at a comparable frequency with potassium chloride, and continuous observation of the readings during the course of the determination can be made. The measurement of the electrical resistance requires to be extremely sensitive (*i.e.*, 1 part in 10,000) and accurate. There must be complete compensation for all reactive effects.

The most suitable frequency is 1—3 kc./sec., and Jones and Bollinger [11] have described a cell which has a reliable cell constant over fairly wide ranges of resistance. These authors overcome errors due to polarisation by platinisation of the electrodes by using a frequency greater than 1 kc./sec.; errors due to the Parker effect are minimised by employing as low a frequency as practicable, widest possible separation of electrodes and filling tubes, and a thermostat bath of low dielectric constant.

The cell and carbon dioxide absorber need to be a single unit to avoid errors due to transfer of alkali.

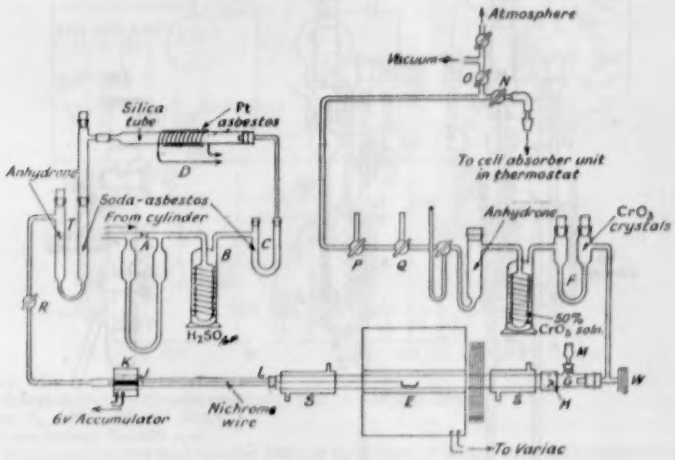
[1] Cain and Maxwell, *Ind. Eng. Chem.*, 1919, **11**, 852.
[2] Kalina and Joseph, *Heat Treatment and Forging*, 1939, **25**, 169.
[3] Ericsson, *Jernkontorets Annaler*, 1944, **128**, 579.
[4] Gardner, Rowland, and Thomas, *Analyst*, 1950, **75**, 173.
[5] Still, Dauncey, and Chirnside, *ibid.*, 1954, **79**, 4.
[6] Gunning and Gordon, *J. Chem. Phys.*, 1942, **10**, 126.
[7] Brönsted and Nielsen, *Trans. Faraday Soc.*, 1935, **31**, 1478.
[8] Kohlrausch, *Z. phys. Chem.*, 1888, **2**, 561.
[9] Parker and Parker, *J. Amer. Chem. Soc.*, 1924, **46**, 312.
[10] Jones and Bradshaw, *ibid.*, 1933, **55**, 1780.
[11] Jones and Bollinger, *ibid.*, 1931, **53**, 411.

Experimental

Apparatus.—The train. Oxygen was supplied from a cylinder with a good-quality reducing valve leading to a venturi-type flowmeter *A* (Fig. 1) followed by a Friederich-type spiral bubbler *B* containing concentrated sulphuric acid. The dried gas, freed from carbon dioxide by soda asbestos contained in a U tube *C*, was passed into a platinised asbestos catalyst chamber *D* kept at 1000° to decompose any hydrocarbons and to cause reaction with any hydrogen. The oxygen then entered the furnace *E* through a drier of "Anhydrone" and a carbon dioxide trap *T* of soda asbestos. Sulphur dioxide was removed from the gas leaving the furnace in two stages by (*a*) a U tube *F* packed with chromic anhydride and (*b*) a Friederich gas-absorption bottle containing a 50% aqueous solution of chromic anhydride. The gas then entered the conductivity cell–absorber unit either directly or *via* the calibration tube.

The furnace. The furnace was a 1" diameter Pythagoras tube 30 in. long, glazed inside. A loading chamber *G* of Pyrex tubing was attached flush to the output end of the furnace by a wide rubber sleeve. The input gases were introduced by means of a long glass tube *L*, which contained a soft-iron slug *J* sealed in a Pyrex envelope. Also sealed into one end of the latter was a semi-rigid nichrome wire which extended into the furnace and was loosely hooked to

Fig. 1.



the combustion boat. The position of the boat could be adjusted therefore by means of the solenoid *K* around the tube *L*, operating on the slug.

Both ends of the furnace were sealed with rubber joints which were protected from the heat of the furnace and the boat by copper cooling fins and water jackets *S,S*. An 18-gauge Kanthal spiral placed as near to the refractory tube as possible heated the furnace. The element was made by winding a suitable length of wire (75 ft.), without distortion or straining, on a clean ¼ in. mandril. Because the Kanthal hardens and embrittles during mechanical working, the spiral was extended slightly, roughly coiled round a 1 in. former, and annealed at 800° for 20 min. by passage of electricity. Six layers of paper were wrapped round the combustion tube, and the spiral was wound accurately in its final position and embedded in alundum cement. When this had hardened, a mullite tube, of 2 in. internal diameter, was cemented over the spiral, and after this cement had set, the inside refractory tube and paper were removed. The compact element was then embedded in tightly packed asbestos and encased in a magnesite brick housing. A "Variac" transformer controlled the temperature (1250—1300° which was found adequate to ignite all the steels). While the apparatus was not in use the furnace was kept at 1000° with a slow stream of oxygen passing through it in order to safeguard the element from damage and to ensure the best performance of the unit.

Thermostat bath. This was an oil-bath regulated by a Lowry-type acetone–mercury regulator and thyratron relay at 25° ± 0·01°.

The cell-absorber unit. The design of this unit (Fig. 2) ensured continuous circulation of the alkali. The solution travelled upwards through 90 cm. of 0·2 mm. capillary spiral *A* which had

been blown into 0·5 mm. bulbs at 2 cm. intervals. The liquid was propelled upwards by the oxygen bubbles injected at the jet *B*. The oxygen was released at the jet *M*, while the alkali proceeded downwards through cup *C* and two-way tap *D* into the cell *E* and back to the base of the spiral *A* *via* tube *K*, the three-way tap *F*, and tube *H*. The cell was filled independently of the absorber, a definite volume of liquid being enclosed between the two taps. There was no "dead" liquid which escaped circulation. *G* served as a filler to provide a head of liquid greater than that at tap *D* until tap *F* was closed to complete the liquid circuit. The extended connection *H* between *F* and *B* prevented passage of gas backwards (*i.e.*, from *B* to *F* and into the cell) owing to back pressure produced by the adsorption spiral. The lead into jet *B* from the train was *via* a B 14 socket *N* and included a trap *J* to contain the alkali in the event of a partial vacuum being produced as a result of too rapid combustion of the sample. The jet *M* curved back almost to the wall of cup *C* to prevent splashing. To make the unit more robust, Polythene bridges (not shown) were employed as braces. The guard tube (Fig. 3) connected into B 19 socket *O*. The dimensions of the cell were: Interelectrode separation, 5 cm.; electrode area, 1 sq. cm.; height of absorption spiral (10 turns), 13 cm.; external diameter of absorption spiral, 3·5 cm.; total volume of liquid enclosed, 18·45 ml.

FIG. 2. (Drawn to scale.)

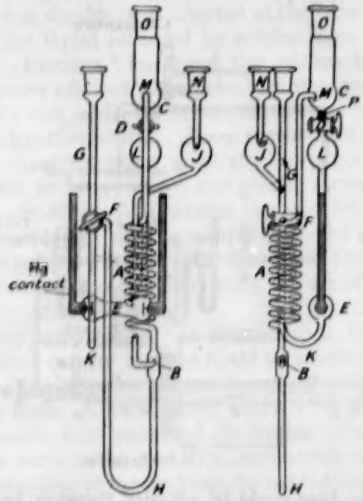
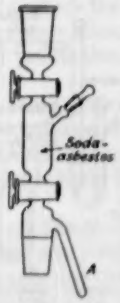


FIG. 3.



Measurement of Cell Resistance.—The electrical circuits used in the cell resistance measurement can be conveniently divided into four parts.

(*a*) *The oscillator and preamplifier.* The oscillator was designed to provide a stable note of about 1 kc./sec. with the minimum of harmonic distortion. A phase-shift circuit was used containing resistance and capacitance only. This system gave a well-defined balance point with distortion of the order of 0·1% only. The amplifier following served primarily to isolate the oscillator from the bridge, but gave ten-fold distortionless amplification. By using small components a very compact arrangement was possible.

(*b*) *The bridge.* Owing to the wide separation of the electrodes and the dilute solutions employed, high resistance readings were often obtained. These were comparable to the impedances to earth of the various bridge sections and introduced errors. The Wagner earth was therefore incorporated to provide, with simple switches and adjustment of a potentiometer and variable condenser, that the ratio arms of the bridge were balanced to earth with respect to resistance and reactance. Switching the cell and variable arm into the bridge circuit then gave a true balance. Reference to Fig. 4 shows that the Wagner earth ensured that points *X* and *Y* had exactly the same impedance to earth, *i.e.*, by placing the switch contacts in position *A* and by adjusting R_1 and C_1 to the point of balance. Placing switch contacts in position *B* included the cell and a balancing decade box R_2 and condenser C_2 while the junction of the ratio-arms was disconnected from earth. The accuracy was then of the required degree.

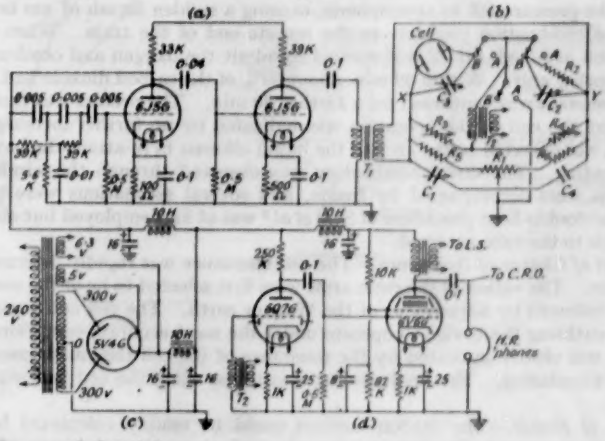
(*c*) *The power pack and* (*d*) *post-bridge amplifier.* These are conventional circuits; indication

of the balance point was given by oscilloscope, loud speaker, or phones, as convenient. In practice ear phones gave a satisfactory balance point.

Manipulation.—Cleaning and drying the cell-absorber unit. Spent alkali was withdrawn with a water-pump and the unit was washed several times with distilled water. The interior of the apparatus was dried by rinsing with acetone followed by a current of air. Silicone stopcock grease was unsatisfactory since the above method of drying soon deposited a water-repelling layer on the interior of the unit which could only be removed by alcoholic potash. With use of a petroleum grease this problem was avoided and periodic cleaning with fuming nitric acid was satisfactory. The electrical connections were made with platinum wire through clean mercury. No amalgamation therefore occurred and the contact tubes remained clean.

Filling the cell-absorber unit. In order to reduce the volume of liquid to a minimum, the cell only was filled, independently of the absorption circuit *HAC* (Fig. 2). Tap *F* was turned to join *G* to the base of cell *E* through *K*. The top of cell *E* communicated directly to tap *D*.

FIG. 4.



R_1, 250 ohms, wire wound rheostat.
R_2, Muirhead non-inductive decade resistance box (1—10,000 ohms).
R_3 and R_4, as R_2, 1000—10,000 ohms.
C_1, Variable condenser, 0—500 $\mu\mu$F.
C_2, Bank of condensers giving multiples of 100 $\mu\mu$F up to 0·01 μF with a variable condenser of 0—500 $\mu\mu$F.
C_3, Bank of condensers, 100 $\mu\mu$F—0·001 μF.
C_4, 200 $\mu\mu$F.
T_1, Wharfedale multi-ratio loudspeaker transformer.
T_2, Transformer, ratio primary : secondary = 1 : 10.

Conductivity water was added through *G* until it exactly reached tap *D*, which was then turned off, care being taken to exclude air bubbles. Tap *F* was turned to a neutral position while the surplus liquid was removed from *G*, which was then stoppered. This gave an exact volume of liquid in the cell. Tap *D* was opened, and tap *F* turned to connect tube *K* with tube *H* and spiral *A*, which filled with liquid while the level fell in bulb *L*.

Preparation of solution. About 1 g. of sodium amalgam (17% Na, w/w) was placed on a glass-wool pad *P*, by means of a glass spatula, and the carbon dioxide guard tube (Fig. 3) replaced. The water was circulated, and its resistance continually checked until a suitable value was given. The gas flow was then stopped, the liquid allowed to drain away from *P*, and the amalgam tipped into the side-tube *A* to be removed later. The alkali was then circulated for 1 hr. to mix it thoroughly. Thus prepared, the alkali was almost carbonate- and silicate-free, but where many determinations were to be made over the same concentration range a stock solution was employed. This alkali was circulated for about 20 min. to ensure complete mixing.

Operating conditions. The head of liquid and the viscous drag encountered as it passed through the capillaries made an initial pressure of about 30 mm. of Hg necessary before circulation could commence. Back diffusion of atmospheric carbon dioxide was eliminated by the

guard tube. Final readings were made when the liquid had attained the bath temperature; normally 10 min. were necessary, and in summer much shorter times sufficed.

Determination of blank. The blank estimation was conducted under conditions exactly comparable with those in an actual estimation; *i.e.*, the boat (Pythagoras unglazed, size h4 or h5) was placed in the hot zone of the furnace, the speed of gas flow (500 ml./hr.) and temperature of the furnace being identical.

Combustion of a steel sample. The optimum quantity of sample was weighed into a special weighing tube fitted with a B 14 cone. The boat was withdrawn slowly from the furnace (Fig. 1), being allowed to cool before it passed over the rubber joint *H* into the loading chamber. A precautionary increase in gas flow ensured an outward movement of gas through the loading tube *M*, which was lowered to the boat as the sample was inserted. The tube was closed by means of a rubber bung and an excess pressure of 100—120 mm. generated in the apparatus before isolation of the furnace by closing taps *R*, *O*, and *N*. The manometer was observed to verify that leaks were absent, and the boat was towed into the furnace. The vigorous combustion of the steel which followed caused the excess pressure to be reduced, and *R* was opened before the pressure fell to atmospheric, causing a sudden inrush of gas into the furnace which swept the combustion products to the remote end of the train. When the operating pressure had been attained, tap *N* was opened to admit the oxygen and combustion products into the cell-absorber unit. Within 30 min. about 80% of the carbon dioxide had been absorbed and the same flow rate was continued for a further 30 min. The process was generally finished by this time, but the end of the operation was indicated by no further increase in resistance. Finally, the gas was diverted to the air and the liquid allowed to re-attain the bath temperature for the final reading. The metal combustion was observed through the window *W*. Satisfactory ignitions were accompanied by fusion, and several estimations were possible in the same boat. The double-boat procedure of Still *et al.*[5] was at first employed but abandoned when no cases of fusion to the tube occurred.

Measurement of Change of Resistance.—The cell resistance was rapidly determined by means of an A.C. bridge. The values of the ratio arms were first selected to be of the same order as the cell resistance, followed by adjustment of the Wagner earth. The cell and variable arms were then included, enabling the bridge to operate under the most accurate conditions. The end of the absorption was clearly indicated by the resistance of the cell remaining constant while the alkali was still circulating. The final reading was taken when the cell had attained the bath temperature.

Calculation of Result.—The carbon content could be readily calculated by reference to calibration curves constructed by burning quantities of sucrose containing *ca.* 100 μg. of carbon in the oxygen stream. The change in cell resistance was plotted against the mean resistance of the cell; the calibration curve is illustrated in Fig. 5.

Carbon content is calculated from the following expression:

$$C(\%) = (R_1 - R_2)/(10 \times \Delta r \times \text{wt. of sample})$$

where R_1 = initial resistance of cell, R_2 = final resistance of cell after deduction of blank, Δr = change of resistance in cell when the carbon dioxide from 100 μg. of carbon is passed through the cell-absorber unit while the mean resistance of the cell = $\frac{1}{2}(R_1 + R_2)$. Δr is obtained from the calibration graph (Fig. 5).

Time required for a Determination.—About 70 min. were required for a determination after the blank was known. Undoubtedly, this is long compared with other methods of comparable accuracy, but the investigation to which this method was applied provided only very small samples.

Calibration.—One method[4,5] is to evaporate known volumes of sugar solution contained in platinum boats over phosphoric oxide in a desiccator, and then to burn off the sugar in the furnace. It was considered more convenient to avoid using the furnace and the following method was adopted.

A sucrose solution containing 100 μg. of carbon in 0·1 ml. of solution was prepared. Small known volumes of this were placed almost half way down the horizontal Pyrex tube *A* (Fig. 6) by means of an "Agla" micrometer syringe, fitted with a 2" needle. The rubber stopper was quickly replaced, and the air withdrawn from the tube through a trap *B* containing phosphoric oxide. The water was removed by gentle heating (inaccurate results were obtained when the water was not removed). Pure oxygen from the train was allowed to enter the tube until the necessary working pressure had been attained to operate the absorber, into which the gases were passed after the trap *B* was removed from their path. The gas flow was continued for 15 min.

in order to sweep all the carbon dioxide out of the calibration tube. The cell liquid was permitted to come to rest and reach the thermostat temperature before the cell resistance was determined. The oxygen flow was restarted, and the tube heated by Bunsen burners at (1) and (2). The heating at (2) was carried out gently, approaching the sugar, so that about 5 min. were needed to burn it off, giving a suitable dilution of the carbon dioxide in the oxygen stream. The heating at (1) was strong and steady and served to burn any volatilised but undecomposed sugar. The final resistance reading was made as described previously. The calibration curve was constructed by plotting the change in cell resistance against the average resistance during the combustion of 100 μg. of carbon. (The values found were reproducible to within ±1%.) Recalibration was only carried out when the cell was cleaned and after every month of continuous daily operation.

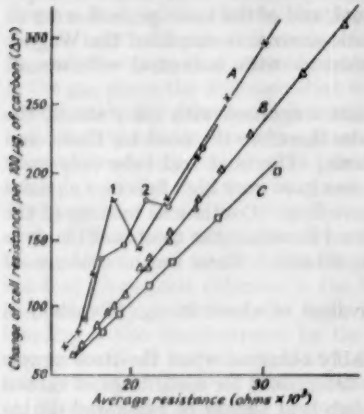
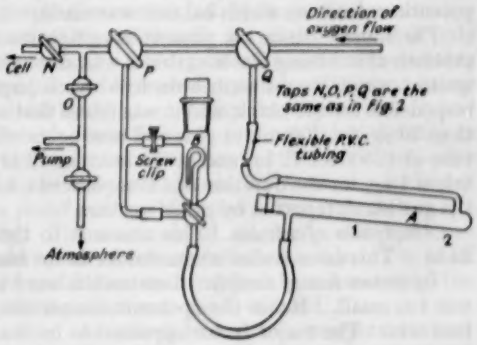


FIG. 5. Solutions, approximately 0·01N of *A*, $Ba(OH)_2$ (×, soln. 1; ○, soln. 2); *B*, NaOH; *C*, LiOH.

FIG. 6.



DISCUSSION AND RESULTS

Factors influencing Accuracy.—Cell constant. Measurements using a preliminary cell absorber unit indicated that the cell constant did not vary by more than 0·05% [(24·76 ± 0·11) × 10^{-4}] when using solutions of potassium chloride over the concentration range 0·002—0·1N, which corresponded to the required working ranges.

Change in equivalent conductance of the solution. In absorbing the carbon dioxide from 100 μg. of carbon the 0·01N-alkali underwent an overall change in concentration of 4·5%. At this dilution the change in equivalent conductivity was only 0·04%. Since this apparatus was calibrated directly against carbon these errors were eliminated.

Choice of alkali. Sodium and lithium hydroxides were employed successfully in the cell-absorption unit, giving calibration curves as indicated in Fig. 5. It was found that up to about 40% of the strength of these alkalis could react with the carbon dioxide before hydrolysis of the carbonate became appreciable, causing the specific change in resistance per 100 μg. of carbon to depart from the calibration curve. Carbon dioxide equivalent to 600 μg. of carbon could be absorbed in the 0·01N-alkali before such hydrolysis occurred. Sodium hydroxide was selected since the use of lithium hydroxide held no advantages. Barium hydroxide often gave erratic results, sometimes much higher than expected, with no apparent connection between the deviations. The results for this alkali are also given in Fig. 5. Similar behaviour was observed by Still *et al.*[5] It was not corrected even when the precipitated carbonate was filtered out of the cell by means of the glass-wool plug *P*.

Evaporation. Still *et al.*[5] found that the evaporation losses were approximately 0·1% of the original volume for a 40-min. determination and it was found possible to carry out two successive determinations in the same alkali solution without adverse effect. In the present investigation evaporation losses for a 60-min. determination amounted to only 0·062% of the volume of the solution. At least four determinations therefore were possible

without refilling. In practice, only two or three were carried out, since the unit could be washed out and refilled very quickly.

In more accurate work it is possible to determine the weight of solution lost, by absorbing in drying tubes and then replacing the lost water by means of an "Agla" micrometer syringe. The present investigation did not merit this degree of accuracy.

Conditions for efficient absorption. The circulation of alkali had to be steady, *i.e.*, it had to move upwards through the spiral at constant speed with regular spacing of bubbles. A flow rate of 500 ml./hr. just permitted this, and greater speeds, *e.g.*, 1 l./hr., were possible without serious loss of accuracy. Lissapol, used by many other workers, caused considerable irregularity in the alkali circulation, and low results were obtained.

Method of making measurement. The most accurate conditions under which a simple bridge circuit can operate is to have the ratio arms equal, and of the same general order as the unknown and variable arms. The use of equal ratio arms also simplified the Wagner earth circuit which comprised two fixed carbon resistors with a central wire-wound potentiometer from which balance was made.

The blank. Since the present investigation was not concerned with alloy steels, the problem of oxidising stable carbides was absent, and also therefore the need for fluxes and igniters which would contribute to a much larger blank. The boat and tube only were responsible for the blank, and it was found that new tubes gave very high figures, *i.e.*, more than 30 μg. for 200 ml. of gas, and new boats often gave 5 μg. Continuous heating of the tube at 1250° for 72 hr. and of the boat for 12 hr. sufficed to reduce the combined blank to below 1 μg. for the duration of a complete run, *i.e.*, 45—60 min. There was no evidence of the gas blank reported by other workers.[5]

Absorption of silicate. This amounts to the equivalent of about 10 μg. of carbon in 24 hr. This error is also accounted for in the blank.

Optimum size of sample. Low results were invariably obtained when the steel sample was too small. Hence the optimum sample size was determined for each range of carbon contents. The major factor appeared to be that enough heat should be generated during combustion to evolve all the carbon dioxide. This determined the minimum size; the maximum was limited by the capacity of the alkali. Generally, 0·3 g. of steel was adequate over the range chosen.

Results.—The precision of the method was satisfactory, since the results given in the Table are reproducible to 1% in general. In order to examine the accuracy of the method,

	B.C.S. Carbon (%)		Conductivity method Carbon (%)	
No.	Range	Average	Values	Average
237	0·080—0·086	0·083	0·0840, 0·0845, 0·0847	0·0843 ± 0·0004
152/1	0·067—0·076	0·072	0·0742, 0·0741, 0·0742	0·0740 ± 0·0004
265	0·043—0·050	0·047	0·0472, 0·0471, 0·0470, 0·0479	0·0473 ± 0·0006
264	0·033—0·040	0·037	0·0375, 0·0379, 0·0373, 0·0375	0·0375 ± 0·0004
149	0·002—0·005	0·004	0·0041, 0·0038, 0·0036, 0·0042	0·0039 ± 0·0003
152	(old sample)	0·1140	0·1130, 0·1125, 0·1128, 0·1122	0·1126 ± 0·0004

determinations of the carbon content of standard low-carbon steels, issued by the Bureau of Analysed Samples, Ltd., were made. The Table shows the average values and the range of the values found by the individual analysts. Comparison of the carbon content found by this conductivity method shows that the average values in all cases lie within the range of the B.C.S. values, but in general appear to be 1—2% above the B.C.S. average. The analysts providing the figures for the B.C.S. values usually employed sample weights of 2—10 g. to give greater accuracy. The low-pressure method (using 0·5-g. sample) appears to yield values 1—3% lower than the B.C.S. average; the earlier conductivity method [6] requires the use of 0·5—2 g. samples for the same order of accuracy. It therefore appears that the method described here gives an order of accuracy comparable with other standard methods, with the advantage that only 0·3—0·5 g. of sample is needed for a determination.

TECHNICAL COLLEGE, NOTTINGHAM. [*Received, September 13th*, 1955.]

[5] Shedlovsky, *J. Amer. Chem. Soc.*, 1930, **52**, 1793.

661. *The Thermal Decomposition of Oxamide.*

By F. M. Tayler and L. L. Bircumshaw.

The thermal decomposition of oxamide, to cyanogen and water, has been studied in the gas phase by use of a static gasometric method, over the temperature range 320—490°. The reaction was found to be of first order and the velocity constant can be expressed by the equation $k = 10^a e^{-b}$, where $a = 10{\cdot}25 \pm 0{\cdot}31$ and $b = (41{\cdot}38 \pm 0{\cdot}94)/RT$. The influence of concentration, surface area of the reaction vessel, and of the presence of nitrogen, cyanogen, and water was examined. The presence of nitrogen gave unusual effects.

From a study of the thermal decomposition of oxamide it was hoped to obtain information on the relative ratio of decomposition in the solid and in the gas phase. Experiment showed, however, that oxamide undergoes a polycondensation in the solid phase and that in the gas phase the decomposition was a simple dissociation into cyanogen and water.

Oxamide has a rather high melting point, 417°, and despite its polar groups it is only very slightly soluble in water. It usually forms a very fine crystalline powder and attempts to grow larger crystals tend to produce complicated branched growths. The crystals are triclinic and the structure has been examined by Misch and Van der Wyk [1] and Duke.[2] The molecules lie flat in parallel planes; in each plane the molecules are linked directly to each of their near neighbours by strong hydrogen bonds to form an infinite sheet—also strong bonding of an undefined type exists between the planes. This strong hydrogen bonding gives great cohesion in the lattice plane and would explain oxamide's high m. p., low solubility in water, and high density. The existence of intermolecular hydrogen bonding is also demonstrated by the Raman spectrum of crystalline oxamide. The band due to the N–H frequencies is at 3141 cm.$^{-1}$ and indicates strong hydrogen bonding of the C=O group and the N–H group in the *cis*-position relative to the C–N bond.

Werner and Carpenter [3] reported that when oxamide is heated to a temperature just sufficient to ensure complete volatilisation, a sublimate of ammonium cyanate, urea, and biuret is formed and ammonia, water, carbon monoxide, and hydrogen cyanide are evolved. The experimental evidence is, however, not very detailed. These authors were hoping to check the results of Williamson [4] who obtained urea by heating oxamide with mercuric oxide. This they were unable to do although they obtained urea by heating oxamide alone.

Experimental

Purification and Analysis of the Oxamide.—The material was obtained from the Ministry of Supply: it all passed through a B.S.S. 200-mesh sieve (13·5 microns), and 90% passed through a 240-mesh sieve (10 microns), this grade being used in the experiments. By the *p*-nitrobenzenediazonium chloride colour test, the material was found to contain 0·2% of ammonium ion. After two crystallisations from water this figure was reduced to 0·001%, and this product was used. The total nitrogen in the oxamide was estimated by the Kjeldahl–Gunning method, and the purity found to be $100{\cdot}02 \pm 0{\cdot}03\%$.

Preliminary experiments showed that the only products of thermal decomposition were cyanogen and water. This was confirmed quantitatively. 0·5 G. samples of the oxamide were accurately weighed into a glass boat placed in the reaction tube between two gauzes. A slow stream of nitrogen was passed through the tube, and the gauzes, heated by two burners, were moved forward until the whole of the oxamide and any products of the decomposition were forced over into a U-trap cooled by liquid air. The operation took about 15 min. and the temperature of the nitrogen reached about 350°. An electrostatic precipitator was included in the system to deal with a certain amount of "smoke" which oxamide easily forms. The precipitator was then removed and a spiral absorber containing N/20-sodium hydroxide solution coupled to the trap. The nitrogen flow was adjusted so that a steady stream of bubbles passed up the spiral.

[1] Misch and Van der Wyk, *Compt. Rend. Soc. Phys. Hist. Nat. Genève*, 1938, **55**, 97.
[2] Ayerst and Duke, *Acta Cryst.*, 1954, **7**, 588.
[3] Werner and Carpenter, *J.*, 1918, **113**, 699.
[4] Williamson, Mémoire, Congrès Scientif. de Venise, 1847.

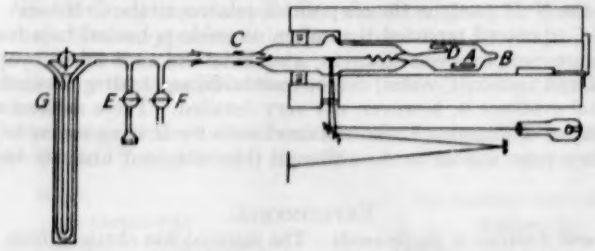
The liquid air around the trap was removed and replaced by a beaker of water; long white crystals of cyanogen could then be seen. These crystals were quickly absorbed in the alkali. Cyanogen was estimated by conductometric titration of the cyanate–cyanide with silver nitrate, Ripan-Tilici's method [5] being used. It was necessary to adjust the pH of the solution to 9·90 ± 0·02 with nitric acid before titration. The presence of any ions capable of reacting with silver nitrate masked the three breaks in the conductivity curve. In all titrations the breaks in the conductivity curve occurred at $\frac{1}{4}$ equiv. ($\frac{1}{2}$ cyanide), $\frac{1}{2}$ equiv. (total cyanide), and equiv. (total cyanide and cyanate), showing that only cyanogen was present in the gases. The oxamide in the U-tube and precipitator was estimated by determining the nitrogen content (Kjeldahl–Gunning method) of the solid collected. The analytical results are given in Table 1. The standard error of these results is 0·3% of the decomposed material and we may assume that the dehydration reaction represents the decomposition of oxamide under these conditions.

TABLE 1.

Oxamide taken (g.)	C_2N_2 found (g.)	Oxamide eq. to C_2N_2 (g.)	Oxamide found (g.)	Total oxamide (g.)	Proportion (%) Decomposed	Not decomp.	Total
0·5007	0·0142	0·0238	0·4769	0·5007	4·75	95·25	100·00
0·4999	0·0338	0·0572	0·4426	0·4998	11·45	88·53	99·98
0·5002	0·0090	0·0152	0·4853	0·5005	3·04	97·0	100·02

The kinetics of the reaction was studied by measuring the pressure rise in a sealed Pyrex glass vessel by means of a glass-spiral gauge used as a null-point instrument; air was admitted to a compensation chamber to balance the pressure due to the reactants, the pressure being read on a mercury manometer. This method was used because oxamide sublimes very readily, making it necessary to have the reaction vessel at one constant temperature with the gauge very slightly hotter. The apparatus is shown diagramatically in Fig. 1. The oxamide (6—15 mg.)

FIG. 1.



was weighed into the small tube *A* and this was dropped down the side tube into the reaction vessel. The tube *A* was sealed at both ends, having a small hole in one side through which the oxamide was introduced. The reaction vessel was evacuated and sealed off at the constriction *B*. The compensation chamber was then evacuated, and the oven brought to the correct temperature. An old reaction vessel and gauge were kept inside the oven between experiments so that the correct temperature distribution could be maintained. The oven had an automatic temperature-control device.

One minute before the start of an experiment the oven current was raised to a maximum and then the disused gauge was removed. The oven was moved over the reaction vessel until the window flange of the gauge touched the " step " inside the furnace tube. The gauge unit was rotated until the light spot was on the scale zero, and the unit was then firmly clamped, at *C*, to the oven trolley. During the initial period of the reaction, the temperature of the vessel was measured with a thermocouple placed at *D*. When the reaction tube was within 5° of the experimental temperature, the oven heating voltage was decreased to its normal value, and the automatic temperature control allowed to function normally. At intervals air was " leaked " into the compensation chamber to bring the light spot back to zero and the pressure was read. Considerable control of this operation was obtained by admitting the air through a sintered-glass filter stick. If the pressure in the reaction vessel exceeded atmospheric, air could be blown in through the tap *F*. At the end of each experiment the gauge unit was opened by cracking

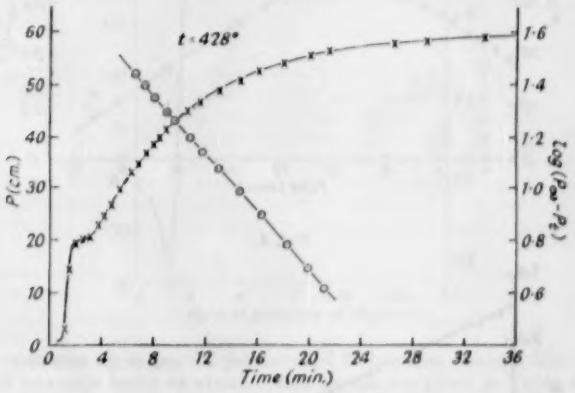
[5] Ripan-Tilici, *Z. anal. Chem.*, 1934, **99**, 415.

the end of the tube at *B*. In a few experiments the decomposition was carried out in an atmosphere of added inert gas; the appropriate pressure was then " leaked " into the apparatus from a storage bulb just before sealing off.

The quantity of oxamide used was usually adjusted to give a final pressure of 40—60 cm. in the 22 c.c. reaction vessel, which was found to be a suitable range for the instrument. The gauges were rather susceptible to vibration, but this was avoided by mounting the whole oven assembly on large pieces of sponge rubber. The mirror on the spiral gauge was front-silvered with aluminium by vacuum sputtering and attached to the glass spindles by fireclay cement. The time taken for the gauge unit to reach the experimental temperature was usually about 3—4 min.

An oven with a rather unusual temperature distribution was required to prevent the oxamide subliming into the spiral, which was kept a little hotter than the reaction vessel. A tubular furnace which completely enclosed the reaction vessel and gauge was constructed. The movements of the mirror were observed through a small window cemented into the side. The oven was 18 in. long with a diameter of 1·5 in. and 3 in. diameter for 3 in. from the window outwards. On this tube was laid a winding of 150 ft. of 24-gauge " Brightway " wire after the core had first been insulated with a layer of refractory cement. On top of this winding two supplementary

FIG. 2.



heaters were placed, one of 22 ft. 24-gauge over 3 in. inwards from the step, and the other 9 ft. over 2 in. at the narrow end of the tube, each winding being separate. The oven was assembled on a trolley which ran on rails so that the oven could be run over the reaction vessel at the beginning of an experiment.

The furnace was controlled by a Sunvic platinum-resistance thermometer controller type R.T.I. The platinum-resistance thermometer was placed inside the narrow end of the furnace tube. With this arrangement the furnace took 2—3 min. to reach the temperature of the experiment and then remained constant to within $\pm 0{\cdot}05°$.

Experiments showed that the oxamide decomposed with a measurable velocity over the temperature range 320—490° at initial pressure of between 14 and 30 cm. In the first minute, as the reaction vessel warmed, there was no pressure rise, but suddenly the pressure increased to that equivalent to the oxamide present; it then steadied for a while but rose again as the vessel reached the reaction temperature, and then rose smoothly to reach a final value of three times the pressure of the original oxamide. The measured values of this final pressure P_∞ were within 2% of the theoretical value. There was very little formation of paracyanogen, the walls of the reaction vessel becoming slightly discoloured after 10—15 experiments.

The reaction followed a first-order law and a plot of $2{\cdot}303 \log (P_\infty - P_t)$ against time gave satisfactory straight lines. One is shown for 428° in Fig. 2. For the determination of these first-order constants, however, Guggenheim's method [6] was used, in which t is plotted against $\log (P_{t+\tau} - P_t)$, τ being a constant time interval greater than the half-life of the decomposing substance.

[6] Guggenheim, *Phil. Mag.*, 1926, **2**, 538.

Influence of Temperature.—The decomposition was followed in the temperature range 300—500° and found to be of first order over the whole range. In Fig. 3 are shown the pressure–time curve and the plot of log $(P_{t+\tau} - P_t)$ against time for 425°. In Fig. 4 $\log_{10} k$ is plotted against $1/T$, and from this graph are calculated the following values: $\log_{10} A = 10{\cdot}25 \pm 0{\cdot}31$, $E = 41{\cdot}38 \pm 0{\cdot}94$ kcal.

Influence of Concentration.—Over the limited initial pressure range of 14—30 cm. the value of the rate constant is unaltered. Owing to experimental difficulties, final pressures measured had to be kept below 90 cm., and final pressures below 40 cm. meant that the errors in reading the pressures became rather large. In Table 2 are given the velocity constants at 405°, the

FIG. 3.

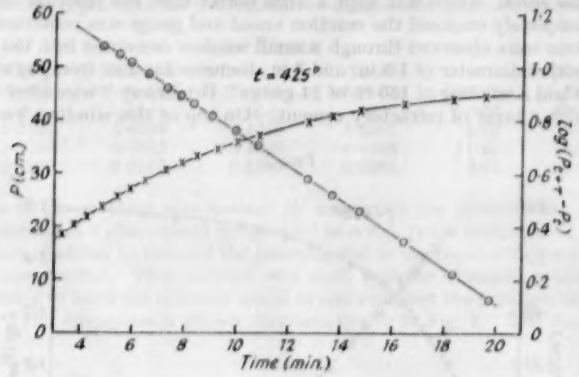
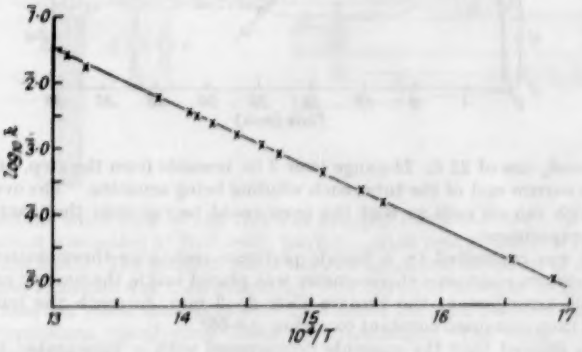


FIG. 4.



standard deviation being ±1·3%, well below the overall experimental accuracy of ±4%. Velocity constants at 428° are also shown.

TABLE 2.

	At 405°						At 428°		
Initial oxamide press. (cm.)	16·1	19·3	21·2	21·8	25·8	26·8	13·9	20·0	23·9
$10^4 k$ (sec.$^{-1}$)	767	779	793	790	770	767	219	230	222

Effect of Increased Area of the Reaction Vessel.—A number of runs were made in which the surface area of the reaction vessel was increased by " packing " it with thin-walled Pyrex glass tubing of 1 mm. diameter. The increase in surface area was about four times that of the original area. Values of the velocity constants at various temperatures for the packed reaction vessel are given in Table 3, corresponding results in unpacked vessels being given in parentheses.

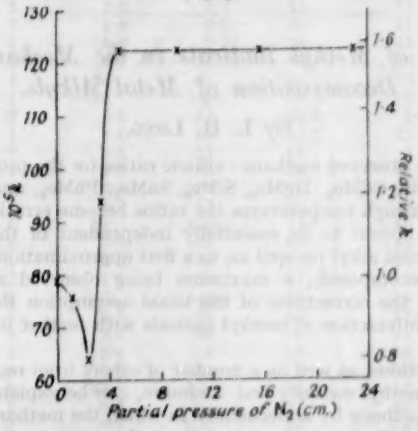
It will be seen that the velocity of the reaction over this range of temperature is unaffected by the ratio of surface to area of the reaction vessel.

TABLE 3.

Temp.	436°	430°	390°	377°	320°
10^5k (sec.$^{-1}$)	334 (333)	275 (242)	39 (39)	21 (21)	1 (1)

Effect of Added Gases.—The effect of nitrogen was first studied. It was introduced into the reaction vessel at pressures from 1·0 to 23·0 cm., the temperature of the experiment being 407° and the partial pressure of the oxamide being 20 cm. (All pressures measured at 407°.) The results are shown graphically in Fig. 5. The reaction remains of first order kinetically; excellent plots of log $(P_{t+\tau} - P_t)$ against time are obtained, and it is seen that small pressures of nitrogen lower the reaction rate slightly but larger pressures increase it appreciably. Above a certain pressure, *ca.* 4·5 cm., the rate becomes practically independent of the nitrogen pressure.

FIG. 5.



The effect of cyanogen up to partial pressures of 28 cm. was studied, the temperature and partial pressure of oxamide being as above. The results are given in Table 4. At the lower

TABLE 4.

Cyanogen pressure (cm.)	0·0	2·3	7·25	14·8	20·6	28·25
10^5k (sec.$^{-1}$)	79	79	79	79	53	57

pressures cyanogen had no effect, but pressures of 20 cm. or more reduced the rate to a small extent. The reaction remained strictly of first order. Had the reverse reaction $C_2N_2 + 2H_2O \rightleftharpoons (CO{\cdot}NH_2)_2$ occurred to a measurable extent the values of the function $P_{t+\tau}$ would be less than expected. The values of $(P_{t+\tau} - P_t)$ would also be lower than the expected figures and so the gradient of the plot of log $(P_{t+\tau} - P_t)$ against time would be steepened, the gradient increase becoming more noticeable as the experiment continued. This effect was not observed, so the reverse reaction was presumed not to occur.

Water vapour was studied up to a pressure of 18 cm., with the following results:

H_2O pressure (cm.)	0·0	2·3	18·4
k (sec.$^{-1}$)	0·00079	0·00079	0·00079

From these, it is assumed that under the experimental conditions outlined the addition of the products of the decomposition has little effect on the course of the reaction.

Discussion.—There is much evidence to show that many first-order gas-phase pyrolysis reactions have free-radical mechanisms, but there is little evidence to show that such a mechanism applies here. The usual tests for thermal free-radical reactions could not be applied since the gases would react with cyanogen.

[7] Howlett, *Trans. Faraday Soc.*, 1952, **48**, 25.

The decomposition of oxamide is apparently homogeneous, so that any chain mechanism would involve radical chains in which chain formation and termination both occur only in the gas phase or only on the walls of the reaction vessel.[7] The presence of nitrogen in the reaction vessel might be expected to increase the reaction rate with a chain mechanism, since the additional collisions would increase the effective length of the chain. The effect is observed to some extent. Nitrogen could only increase the rate if termination was on the walls, any chain mechanism must therefore involve wall initiation and termination only.

There is no obvious possible radical-chain mechanism for the decomposition of oxamide. The low value, $10^{10\cdot25}$, of the temperature-independent factor suggests that the rate-controlling step does not involve the breaking of a single bond to give radicals which normally requires a factor of 10^{13}.

Dept. of Chemistry, The University,
Edgbaston, Birmingham, 15.

[*Received, December 12th*, 1955.]

---

662. *The Fate of Methyl Radicals in the Mechanism of Thermal Decomposition of Metal Alkyls.*

By L. H. Long.

Study of the observed methane : ethane ratios for the products of decomposition of AgMe, $CdMe_2$, $HgMe_2$, $SiMe_4$, $SnMe_4$, $PbMe_4$, and $AsMe_3$ reveals that, whereas at high temperatures the ratios become erratic, at lower temperatures they appear to be essentially independent of the nature of the decomposing metal alkyl (as well as, to a first approximation, of the pressure and fraction decomposed), a maximum being observed at ~340°. This casts doubt on the correctness of the usual assumption that the methane arises through interaction of methyl radicals with further metal alkyl molecules.

The observations, as well as a number of others from recent work on the pyrolysis of dimethyl-mercury and -cadmiun, can be explained with greater economy of hypothesis by a mechanism in which the methane arises through the reaction of methyl radicals among themselves, not on a first collision but in a series of subsequent steps, all of which are to be associated with more favourable activation energies and steric factors.

Although a variety of mechanisms of pyrolysis have been proposed for a number of metal alkyls, no comprehensive theory has so far been propounded. It has frequently been *assumed* that the alkyl radicals liberated by the initial decomposition are completely accounted for by hydrogen-abstraction reactions with further molecules of the compound being pyrolysed, in the manner not uncommonly observed in the case of other kinds of organic compounds. Evidence recently obtained from studies of dimethylmercury [1] and dimethylcadmium [2] do not accord with such an assumption, however, so that a fresh examination of the available facts concerning the other metal alkyls is timely. For simplicity, attention is here restricted to methyl compounds. No claim is made that this paper in any way establishes a new general decomposition scheme for metal methyls, but certain regularities are pointed out for the first time, while the mechanism suggested is able to explain the observed data in a simple and reasonable manner.

The Available Evidence.—The results of all investigations of metal methyls in the vapour phase so far published in suitable form and with sufficient detail for useful comparison are included in Table 1. (Further data are available for dimethylcadmium,[13] but are erratic through a pronounced surface effect and are not expressed in a suitable form.) Only results of pyrolysis studies in "static" systems are tabulated, as the flow technique demands excessively high temperatures and fast rates of reaction. Also excluded are the results of experiments in which <1% decomposition was effected or in which the metal alkyl vapour

[1] Laurie and Long, *Trans. Faraday Soc.*, 1955, **51**, 665.
[2] Laurie and Long, to be published.

was adulterated. As the temperature region below 250° is not represented by any vapour-phase pyrolysis data, one result for solid methylsilver at −40° in an inert solvent, and a series of photolysis results for dimethylmercury over the range 100—240° have been added. The composition of the decomposition products from photolyses is materially dependent on the intensity of irradiation, so that only low-intensity runs are included in Table 1,

TABLE 1. *Pyrolysis of metal alkyls. Content of methane and ethane in gaseous products.*

Alkyl	Temp.	No. of runs averaged	Initial concn. (mmole/l.)	% decomposed	% CH_4	% C_2H_6	CH_4/C_2H_6	Ref.
* AgMe	−40°	—	—	100	0	100	0·00	3
† $HgMe_2$	100	1	1·6	1·8	4	96	0·04	4
† $HgMe_2$	125	2	1·6	2·0	9	91	0·1	4
† $HgMe_2$	150	1	1·6	2·0	17	83	0·2	4
† $HgMe_2$	175	1	1·6	1·9	25	75	0·3	4
† $HgMe_2$	200	1	1·6	2·2	39	61	0·6	4
† $HgMe_2$	240	1	1·6	3·0	59	41	1·4	4
$CdMe_2$	258	4	4·7	46	69	26	2·7	2
$PbMe_4$	265	1	24	?	65	22	3·0	5
$PbMe_4$	295	1	35	high	69	23	3·0	5
$AlMe_3$	298	2	5·4	22	98·6	1·4	70	6
$HgMe_2$	302	1	1·4	45	73 ‡	27 ‡	2·7 ‡	7
$HgMe_2$	303	6	2·2	23	93	3	31	1
$HgMe_2$	305·5	4	2·3	13	69	12	5·8	8
$HgMe_2$	312	1	0·8	100	75	24	3·1	9
$AlMe_3$	313	1	1·7	27	92	3	31	6
$PbMe_4$	315	1	34	high	79	16	4·9	5
$HgMe_2$	323·5	2	3·0	13	68	13	5·2	8
$HgMe_2$	330	1	0·8	100	77	23	3·3	9
$AlMe_3$	334	2	1·6	62	97	1·5	65	6
$PbMe_4$	340	1	35	high	86	8	11	5
$HgMe_2$	342	5	2·3	28	65	17	3·8	8
$HgMe_2$	346	5	2·2	36	80	14	5·7	1
$HgMe_2$	348	2	2·4	73	85	15	5·7	7
$HgMe_2$	350·5	1	0·8	100	77	23	3·3	9
$PbMe_4$	365	1	48	high	82	12	6·8	5
$HgMe_2$	370	1	0·8	100	71	30	2·4	9
$HgMe_2$	385	1	0·7	100	66	34	1·9	9
$PbMe_4$	395	1	46	high	74	19	3·9	5
$HgMe_2$	401	1	0·7	100	60	40	1·5	9
$AsMe_3$	410	1	4·3	100	91	5	18	10
$AsMe_3$	440	2	3·0	100	88	7	12	10
$PbMe_4$	440	1	18	high	52	39	1·3	5
$SnMe_4$	485	4	2·1	57	83	0	∞	11
$PbMe_4$	550	1	14	100	23	23	1·0	5
$PbMe_4$	620	1	13	100	28	20	1·4	5
$SiMe_4$	659	1	?	?	58	0	∞	12
$SiMe_4$	689	2	?	?	59	0	∞	12

* Solid methylsilver suspended in methanol. † Photolysis runs (low intensity).
‡ Accuracy stated to be low.

these most nearly resembling the conditions of low radical concentration obtaining in " static " pyrolysis systems.

The pyrolysis results mostly lie in the range 250—450°. The initial pressures of vapour employed have, for easier comparison, been converted into concentrations (col. 4), while

[3] Semerano and Riccoboni, *Z. phys. Chem.*, 1941, *A*, **189**, 203.
[4] Rebbert and Steacie, *Canad. J. Chem.*, 1953, **31**, 631.
[5] Simons, McNamee, and Hurd, *J. Phys. Chem.*, 1932, **36**, 939.
[6] Yeddanapalli and Schubert, *J. Chem. Phys.*, 1946, **14**, 1.
[7] Cunningham and H. S. Taylor, *ibid.*, 1938, **6**, 359.
[8] Yeddanapalli, Srinivasan, and Paul, *J. Sci. Ind. Res.* (*India*), 1954, **13**, *B*, 232.
[9] Pellin, Thesis, University of Connecticut, 1953; Univ. Microfilms (Ann Arbor, Michigan), Doctorial Dissertation Series, Publ. No. 6336.
[10] Ayscough and Emeléus, *J.*, 1954, 3381.
[11] Waring and Horton, *J. Amer. Chem. Soc.*, 1945, **67**, 540.
[12] Helm and Mack, *ibid.*, 1937, **59**, 60.
[13] Heller and H. A. Taylor, *J. Phys. Chem.*, 1953, **57**, 226.

the extent to which the decomposition had been allowed to proceed is indicated in col. 5. Cols. 6 and 7 reproduce the molar % of methane and ethane, respectively, in the gaseous products (solids and condensable substances being ignored for this purpose), and col. 8 gives their ratio.

Discussion.—The results being viewed as a whole, it is apparent that the percentages of methane and ethane in the gaseous products depend mainly on temperature, and are almost independent of concentration (which varies by a factor of ~50), of the percentage decomposition, and—except in a few runs—even of the nature of the metal alkyl at temperatures up to about 350°.

The three results for trimethylaluminium exhibit anomalously high methane : ethane ratios. The reason for this is not far to seek. Whereas all the other methyl compounds listed are believed to decompose by a first-order law, the decomposition of trimethylaluminium accords [6] with an order of 1½. That this difference in order is genuine is supported by the observation that the gaseous products of photolysis of trimethylaluminium at 29° and at 120° include unusually large proportions of methane, namely 26 and 43% respectively, while photolysis near room temperature of other metal methyls yields almost pure ethane with only very little methane. This suggests that trimethylaluminium, in contrast to the other metal methyls considered here (see later), has a low activation energy for the hydrogen-abstraction reaction :

$$CH_3 + Al(CH_3)_3 \longrightarrow CH_4 + (CH_3)_2AlCH_2$$

a fact immediately explicable in terms of the pronounced acceptor properties of aluminium, which would facilitate attack at the central atom, particularly by a radical possessing a non-bonding electron. The only other outstandingly high methane : ethane ratio appearing in the Table is that for dimethylmercury at 303° due to Laurie and Long,[1] but a different explanation is found for this (see later).

In view of the various experimental conditions and the approximate nature of some of the results—many of them do not even rest on a full gas analysis—the degree of concordance exhibited up to about 350° is striking. Trimethylaluminium being ignored, the variation observed in the proportions of methane and ethane produced on passing from compound to compound is no greater than that for the single compound most studied, namely dimethylmercury. As the temperature rises, the proportion of ethane—which at lower temperatures is almost the exclusive product—decreases while that of methane increases until it reaches a maximim value of ~80—90%. Just below 350° the trend is reversed and at appreciably higher temperatures the proportions of both methane and ethane become erratic and unpredictable, exhibiting in this temperature region an obvious dependence on the nature of the metal alkyl decomposing. At the same time other gases such as hydrogen and acetylene frequently appear in important amounts. The trend in the methane : ethane ratio is more easily seen in Table 2, in which the results of two

TABLE 2. *Variation of methane/ethane ratio with temperature.*

(*a*) $HgMe_2$, concn. 0·71—0·82 mmole/l. After Pellin [9]				(*b*) $PbMe_4$, concn. 14—48 mmole/l. After Simons *et al.*[5]			
Temp.	% CH_4	% C_2H_6	CH_4/C_2H_6	Temp.	% CH_4	% C_2H_6	CH_4/C_2H_6
312·0°	75·4	24·3	3·22	265°	65·1	21·7	3·0
330·0	76·5	23·3	3·28	295	68·9	22·9	3·0
350·5	76·9	23·0	3·34	315	78·5	15·7	5·0
370·0	70·9	29·8	2·38	340	86·1	7·8	11·0
384·8	66·0	33·9	1·95	365	82·2	11·6	7·1
401·0	59·6	40·1	1·49	395	74·2	18·5	4·0
				440	51·9	38·9	1·3
				550	22·6	22·6	1·0
				620	27·7	19·9	1·4

series of experiments are separated. Although they refer to two different compounds and the pressures employed in one case are about 50 times those in the other, the maximum in the ratio occurs at the same temperature, namely about 340°.

These observations strongly suggest a common circumstance, namely that below this temperature the formation of methane and ethane is to be accounted for by the interaction

of the methyl radicals alone without any important contribution from hydrogen-abstraction processes involving undecomposed metal alkyl molecules. No other assumption will explain all the facts with such economy of hypothesis.

That this assumption is in direct contrast to the assumptions usually made is most readily seen by reference to the mechanisms previously proposed for dimethylmercury. All workers agree that in both pyrolysis and photolysis methyl radicals are split off, either simultaneously or in successive steps, and that a good proportion of them combine to form ethane :

$$\begin{aligned} Hg(CH_3)_2 &\longrightarrow CH_3 + HgCH_3 \\ HgCH_3 &\longrightarrow CH_3 + Hg \\ 2CH_3 &\longrightarrow C_2H_6 \end{aligned}$$

There is no reason to doubt the correctness of this. However, even for the temperature region below 340°, it is usually assumed, without proof, that the observed methane is produced by interaction of methyl radicals with further dimethylmercury molecules :

$$\begin{aligned} CH_3 + Hg(CH_3)_2 &\longrightarrow CH_4 + CH_2{\cdot}Hg{\cdot}CH_3 \\ CH_3 + CH_2{\cdot}Hg{\cdot}CH_3 &\longrightarrow C_2H_5{\cdot}Hg{\cdot}CH_3 \\ 2CH_2{\cdot}Hg{\cdot}CH_3 &\longrightarrow (CH_2{\cdot}Hg{\cdot}CH_3)_2 \end{aligned}$$

One obvious difficulty is that at, say, 300° the main product is methane but the reaction is still of first order and hence not a chain reaction. In this mechanism it is therefore necessary further to assume that the $CH_2{\cdot}Hg{\cdot}CH_3$ radicals do not decompose to liberate methyl radicals—for this would establish a radical chain mechanism incompatible with the observed order of reaction—but survive until they combine with a methyl or secomd $CH_2{\cdot}Hg{\cdot}CH_3$ radical, as indicated. A second suggestion which has been made in attempting to account for certain photolysis results not entirely explicable by the foregoing mechanism is that methyl radicals and dimethylmercury molecules also form an "addition complex" which then reacts further :

$$\begin{aligned} CH_3 + Hg(CH_3)_2 &\rightleftharpoons CH_3{\cdot}Hg(CH_3)_2 \\ CH_3 + CH_3{\cdot}Hg(CH_3)_2 &\longrightarrow \textit{either } C_2H_6 + Hg + 2CH_3 \\ &\quad \textit{or } C_2H_6 + HgCH_3 + CH_3 \\ &\quad \textit{or } C_2H_6 + Hg(CH_3)_2 \end{aligned}$$

Again it is necessary to suppose that the "addition complex" $CH_3{\cdot}Hg(CH_3)_2$ survives and does not react until it encounters another methyl radical.

Neither of these two sets of assumptions, which have been made to avoid postulating a chain mechanism, is satisfactory from the standpoint of economy of hypothesis. A second objection is that the only methane-producing process proposed is one which involves the abstraction of a hydrogen atom from a metal methyl molecule, and so will have an activation energy that will change from compound to compound according to the electronegativity of the central atom; but from Table 1 it is clear that no reflection of any change in activation energy is to be detected in the proportions of methane and ethane produced. Thirdly, it has been generally overlooked that an alternative methane-producing process can be postulated, namely :

$$CH_3 + C_2H_6 \longrightarrow CH_4 + C_2H_5$$

Omission to consider this reaction is serious, because hydrogen abstraction should proceed with a lower activation energy from ethane than from the metal methyls. It is true that activation energies have been estimated for only a few of these compounds in metathetical reactions with methyl radicals, but as far as the available evidence extends, it supports this expectation. The estimates for dimethylmercury are compared with the surprisingly sparse data for ethane in Table 3. The figures for dimethylmercury are in rather poor agreement, but apart from Gomer and Noyes's work, which has been questioned by other workers and also rests on rather bold assumptions as to reaction mechanism, the consensus of opinion is that the activation energy lies in the region 11—15 kcal. Inasmuch as the estimates rest on formation of methane without correction for the methane-producing process $CH_3 + C_2H_6 \longrightarrow CH_4 + C_2H_5$, they will be low, so that the true activation is

more likely to lie in the region 13—15 than 11—13 kcal. The only estimate for the corresponding reaction with dimethylcadmium [21] likewise places the activation energy at ~14 kcal. Relative to hydrogen-abstraction reactions for simple hydrocarbons these figures are high, but that is not surprising for methyl compounds of elements of such low electronegativity as cadmium and mercury. The less electrophilic the central atom, the more

TABLE 3. *Activation energies of hydrogen-abstraction reactions.*

Activation energy (kcal.)	Investigators	Activation energy (kcal.)	Investigators
(*a*) Reaction $CH_3 + Hg(CH_3)_2 \longrightarrow CH_4 + {\cdot}CH_2{\cdot}Hg{\cdot}CH_3$:			
11·6	Thompson and Linnett [14]	11	Gomer and Noyes [16] as corrected by Phibbs and Darwent [17]
13	Cunningham and H. S. Taylor [7]		
13—14	Saunders and H. A. Taylor [15]	10·8	Rebbert and Steacie [4]
9	Gomer and Noyes [16]	15	Yeddanapalli *et al.*[8]
(*b*) Reaction $CH_3 + C_2H_6 \longrightarrow CH_4 + C_2H_5$:			
8·3	Smith and H. S. Taylor [18]	10·4	Trotman-Dickenson and Steacie [19, 20]

will it release electrons to the attached alkyl groups, so increasing the density of the electron cloud surrounding the methyl groups. This, by enhancing the potential barrier to be surmounted by the attacking methyl radical, will serve to increase the energy of activation of the metathetical process. With ethane the energy of activation is only 8—10 kcal. (Table 3), that is to say, some 5 kcal. lower.

This circumstance will mean that the latter reaction is very much faster, especially since ethane will as the simpler molecule also have a decidedly more favourable steric factor. Consequently, in the competition for methyl radicals, ethane, which is inevitably present where methyl radicals are to be found, would be expected to account for the fate of an overwhelming proportion of radicals. We conclude therefore that it is the presence of ethane which is largely responsible for formation of methane, and at not too high temperatures will be virtually exclusively so. Other reasons for this conclusion, based on observations on the behaviour of decomposing dimethylmercury, have been presented in detail elsewhere.[22] Now the same solution is seen to explain simply the otherwise surprising observation that almost all the metal methyls so far studied decompose in accordance with a first-order law. It also explains neatly the unexpected similarity in methane : ethane ratios produced by decomposition of the various compounds at a fairly low temperature.

The Proposed Mechanism.—It is now necessary to draw up a new mechanism to account for the fate of the methyl radicals liberated by those metal methyl compounds that decompose in accordance with a first-order law. A mechanism is possible in which the methane is produced entirely from the methyl radicals, not on the first collision, but in a series of steps, of which the following are probably the most important :

$CH_3 + CH_3 \longrightarrow C_2H_6$	$E = 0$ kcal.
$CH_3 + C_2H_6 \longrightarrow CH_4 + C_2H_5$	$E = 8$—10 kcal.
$CH_3 + C_2H_5 \longrightarrow C_3H_8$	$E = 0$ kcal.
$CH_3 + C_3H_8 \longrightarrow CH_4 + C_3H_7$	$E = 6$—8 kcal.
$C_3H_7 \longrightarrow CH_3 + C_2H_4$ (polymerises)	

All of these steps are associated with comparatively low activation energies and are therefore reasonable. The propane formed at an intermediate stage has actually been observed in traces,[4] but will have no opportunity to build up a sizeable concentration as it reacts

[14] Thompson and Linnett, *Trans. Faraday Soc.*, 1937, **33**, 874.
[15] Saunders and H. A. Taylor, *J. Chem. Phys.*, 1941, **9**, 616.
[16] Gomer and Noyes, *J. Amer. Chem. Soc.*, 1949, **71**, 3390.
[17] Phibbs and Darwent, *Canad. J. Res.*, 1950, *B*, **28**, 395.
[18] Smith and H. S. Taylor, *J. Chem. Phys.*, 1939, **7**, 390.
[19] Trotman-Dickenson and Steacie, *J. Amer. Chem. Soc.*, 1950, **72**, 2310.
[20] Trotman-Dickenson, Birchard, and Steacie, *J. Chem. Phys.*, 1951, **19**, 163.
[21] Anderson and H. A. Taylor, *J. Phys. Chem.*, 1952, **56**, 498.
[22] Long, *Trans. Faraday Soc.*, 1955, **51**, 673.

with methyl radicals very much faster than does ethane, which unlike propane possesses no secondary hydrogen atoms. The resultant propyl radicals are known to be unstable (as are all higher alkyl radicals) and, at the temperatures employed, to split up spontaneously in the manner indicated, while ethylene polymerises in the presence of free radicals.

It is now possible to see why the methane : ethane ratio hardly varies for metal alkyls decomposing at widely different absolute rates, even though formation of methane is of first order with respect to methyl, while formation of ethane (owing to its heterogeneous and homogeneous components) has an order lying between 1 and 2 with respect to methyl. For static systems the temperature is so chosen that a suitable fraction of the alkyl decomposes during a conveniently measurable run, of duration usually 1—10 hours. The rates of release of methyl radicals will therefore only vary over a restricted range lying within a single power of ten from the mean. But since the faster the ethane is formed the faster it will be consumed by other methyl radicals, what matters is not its initial rate of formation, but its equilibrium concentration (for most of it is consumed). And since this is low at the temperature employed in the static system (say 320°), a moderate change in the rate of radical release will in practice affect the equilibrium concentration by at most a few per cent. It follows that, to a first approximation, the methane : ethane ratio will be independent of the initial concentration and percentage decomposition as well as of the nature of the decomposing alkyl, a state of affairs not predicted by any of the older mechanisms.

More direct evidence against the manner of methane formation assumed by other workers is to be found in the pyrolysis study by Gowenlock, Polanyi, and Warhurst, who used a flow technique.[23] They observed that the addition of ethane greatly increased the proportion of methane formed, but did not affect the rate of decomposition of dimethylmercury. Although the authors offer no explanation, this observation not only suggests an important reaction between methyl radicals and ethane (as now proposed), but demonstrates that hydrogen-abstraction from dimethylmercury by methyl radicals does *not* occur to a measurable extent; and since this is true at 552°, it will also hold for the lower temperatures employed in static systems.

It is not claimed that the foregoing mechanism represents the complete picture embracing all the steps. Evidence for these and other, probably less important, processes—such as $CH_3 + C_2H_5 \longrightarrow CH_4 + C_2H_4$ (polymerises); $C_2H_5 + C_2H_5 \longrightarrow C_4H_{10}$ *or* $C_2H_6 + C_2H_4$ (polymerises); $CH_3 + C_4H_{10} \longrightarrow CH_4 + C_4H_9$; $C_4H_9 \longrightarrow C_2H_5 + C_2H_4$ (polymerises) *or* $CH_3 + C_3H_6$ (polymerises)—is discussed more fully elsewhere[22] for the specific case of dimethylmercury. It is striking support for the theory that the different trains of reasoning now advanced lead to essentially identical conclusions.

The net effect of all these processes, whatever the relative importance of the possible paths, is the conversion of $2CH_3$ into $CH_4 + CH_2$ (polymerised); and here further support for the mechanism is to be found in the observation that methane and a relatively non-volatile CH_2 polymer are the principal products obtained in essentially equivalent amounts in the pyrolysis of dimethylmercury [1,7] and dimethylcadmium.[2] Residual ethane and ethylene are also to be expected and are in fact observed. Thus in the case of dimethylmercury, the composition of the gaseous products observed by Laurie and Long [1] at 303° was: CH_4, 93%; C_2H_6, 3%; C_2H_4, 4%. These figures correspond to a methane : ethane ratio of >30 : 1, which is much higher than that observed by other workers. Thus Yeddanapalli, Srinivasan, and Paul [8] found 5·8 : 1 at 305·5° and Pellin [9] 3·1 : 1 at 312°. The main reason for this discrepancy probably lies in the nature of the surface. Thus Pellin did not clean his reaction vessel between the individual runs whereas Yeddanapalli *et al.* did, while Laurie and Long took the further precaution of baking it out under vacuum for 1 hr. at 350°. The importance of this procedure is to be stressed. The recombination of methyl radicals to form ethane is partly a wall reaction, so that a surface which is not scrupulously clean would affect the *fate* of the methyl radicals (though not the rate of their production by a homogeneous unimolecular process) in trapping larger numbers and favouring ethane formation against that of methane. The inference is that surface effects are to a greater or smaller extent responsible for such irregularities in the methane : ethane

[23] Gowenlock, Polanyi, and Warhurst, *Proc. Roy. Soc.*, 1953, *A*, **218**, 269.

ratios as are apparent in Table 1. But for these the concordance would doubtless be even more striking. (At higher temperatures it is apparently less important to bake out the reaction vessel, as shown by the close agreement of the results of Laurie and Long [1] at 346° with those of Cunningham and H. S. Taylor [7] at 348°.)

The foregoing mechanism relates solely to temperatures less than 340°. Above this temperature a new process becomes important, as shown by a decrease in the methane : ethane ratio (Table 2); Laurie and Long [1] found evidence for a change in the mechanism at or very close to this temperature, in that the slope of the Arrhenius plot for the decomposition of dimethylmercury changed sharply between 333° and 343°. There is at present not sufficient evidence to indicate the nature of this new process, but the experimental data of Pellin [9] and of Gowenlock *et al.*[29] indicate that for dimethylmercury it is not the establishment of a radical chain mechanism in the region 350—600°. At still higher temperature it is probable that the metal methyl molecules generally play a more complicated role in the decomposition in "static" systems than that of merely splitting off methyl radicals. This is strongly implied by the erratic methane : ethane ratio above 400° (Table 1).

The author is indebted to the Department of Scientific and Industrial Research for a Special Grant.

THE UNIVERSITY, EXETER. [*Received, January 16th*, 1956.]

---

663. *Perfluoroalkyl Derivatives of Nitrogen. Part III.* Heptafluoronitrosopropane, Perfluoro-2-n-propyl-1 : 2-oxazetidine, Perfluoro(methylene-n-propylamine), and Related Compounds.*

By D. A. BARR and R. N. HASZELDINE.

The preparation and physical and spectroscopic properties of pure heptafluoronitrosopropane are described. This compound reacts with aqueous base to give trifluoroacetic and pentafluoropropionic acid, with oxygen to give heptafluoronitropropane, with active carbon to give perfluoro-1 : 1′-azoxypropane, and with tetrafluoroethylene to give perfluoro-2-*n*-propyl-1 : 2-oxazetidine and a polymer $[\cdot N(C_3F_7)\cdot O\cdot CF_2\cdot CF_2\cdot]_n$. Pyrolysis of the oxazetidine or of the polymer gives, quantitatively, equimolar amounts of perfluoro(methylene-*n*-propylamine), $C_3F_7\cdot N{:}CF_2$, and carbonyl fluoride; the pyrolyses are considered to involve elimination of carbonyl fluoride from a perfluoroalkoxy-radical, and other examples of this general reaction are cited. Mechanisms for the formation of the oxazetidine and the polymer and for the reaction of perfluoro(methylene-*n*-propylamine) with water are considered. Controlled hydrolysis of the compounds $C_3F_7\cdot N{:}CF_2$ and $CF_3\cdot N{:}CF_2$ yields the *iso*cyanates $C_3F_7\cdot NCO$ and $CF_3\cdot NCO$.

THE first general method for the preparation of perfluoronitrosoalkanes [1] involved the free-radical reaction of a perfluoroiodoalkane with nitric oxide in presence of mercury. The development of more convenient experimental techniques for this type of reaction [2] has made the nitroso-compounds readily available, and heptafluoroiodopropane has now given heptafluoronitrosopropane in excellent yield (75—80%). The latter product is more readily purified and, in particular, only very small amounts of pentafluoronitrosoethane and trifluoronitrosomethane are produced by degradation of the fluorocarbon chain. Improved physical properties are reported for heptafluoronitrosopropane.

Banus [3] confirmed the synthesis of heptafluoronitrosopropane, but reported that it decomposed spontaneously at room temperature, faster in the gas phase. Since this last

* Part II, *J.*, 1955, 2532. Part I, *J.*, 1955, 1881, where references to earlier related work are given.

[1] Haszeldine, *Nature*, 1951, **168**, 1028; *J.*, 1953, 2075.

[2] Barr and Haszeldine, *J.*, 1955, 1881; Haszeldine and Mattinson, *Chem. and Ind.*, 1956, 81; Haszeldine and Jander, *J.*, 1954, 696.

[3] Banus, *J.*, 1953, 3755.

report was at variance with our original observations, the stability of heptafluoronitrosopropane has been re-examined carefully. Our original observations have been fully confirmed and heptafluoronitrosopropane is not unstable. It undergoes no reaction on storage in Pyrex apparatus or on contact with mercury, whereas moist soda-glass surfaces, bases, or light rapidly cause decomposition. Trifluoronitrosomethane, which was also reported to be unstable,[3] is similarly stable [1,2] provided that these precautions are taken. Light converts trifluoronitrosomethane into the orange dimer $(CF_3)_2N{\cdot}O{\cdot}NO$.[2]

The vapour-pressure equation, determined for a highly purified sample, leads to a value of 22·6 for Trouton's constant for heptafluoronitrosopropane. Heptafluoronitrosopropane is thus not strongly associated, as was concluded [3] from an apparent Trouton's constant of 28. Analytically and spectroscopically pure perfluoronitrosoalkanes show normal Trouton's constants, *e.g.*, $CF_3{\cdot}NO$ 21·9,[4] $C_2F_5{\cdot}NO$ 22·0, $C_3F_7{\cdot}NO$ 22·6, as do all the other perfluoroalkyl derivatives of nitrogen so far investigated, and there is as yet no legitimate evidence for marked association of liquid or vapour.

Perfluoroalkoxy-radicals.—Some breakdown of the perfluoroalkyl chain occurs during the preparation of heptafluoronitrosopropane. Over-irradiation increases the breakdown, and pentafluoronitrosoethane and trifluoronitrosomethane are then formed in 4 and 2% yield respectively. Perfluoro-*n*-hexane (27%) is also a product, and heptafluoronitropropane, pentafluoronitroethane, and trifluoronitromethane can be detected spectroscopically. These products support the free-radical mechanism proposed for the reaction [1] and also the idea that perfluoroalkoxy-radicals break down by loss of carbonyl fluoride to give a perfluoroalkyl radical containing one fewer carbon atom.[5,6] The formation of a perfluoroalkoxy-radical during the reaction of a perfluoroiodoalkane with nitric oxide very probably occurs by reaction of the perfluoroalkyl radical with nitrogen dioxide, which is present under non-optimum conditions, to give a perfluoroalkyl nitrite; this decomposes by O–N fission to give nitric oxide and a perfluoroalkoxy-radical which then loses carbonyl fluoride to give a perfluoroalkyl radical of shorter chain length:

$$C_3F_7I \xrightarrow{h\nu} C_3F_7{\cdot} + I{\cdot} \xrightarrow{Hg} HgI_2$$

(i) Formation of nitroso-compound:

$$C_3F_7{\cdot} + NO \longrightarrow C_3F_7{\cdot}NO$$

(ii) Dimerisation:

$$2C_3F_7{\cdot} \longrightarrow C_6F_{14}$$

(iii) Formation of nitro-compounds:

$$C_3F_7{\cdot} + NO_2 \longrightarrow C_3F_7{\cdot}NO_2$$

(iv) Formation of nitrite:

$$C_3F_7{\cdot} + NO_2 \longrightarrow C_3F_7{\cdot}O{\cdot}NO$$

(v) Chain degradation *via* alkoxy-radical:

$$C_3F_7{\cdot}O{\cdot}NO \xrightarrow{h\nu} C_3F_7{\cdot}O{\cdot} + NO$$

$$C_3F_7{\cdot}O{\cdot} \longrightarrow C_2F_5{\cdot} + COF_2$$

$$C_2F_5{\cdot} + NO \longrightarrow C_2F_5{\cdot}NO$$

$$C_2F_5{\cdot} \xrightarrow{NO_2} C_2F_5{\cdot}O{\cdot}NO \xrightarrow{h\nu} C_2F_5{\cdot}O{\cdot} \longrightarrow CF_3{\cdot} + COF_2 \xrightarrow{NO} CF_3{\cdot}NO$$

$$CF_3{\cdot} \xrightarrow{NO_2} CF_3{\cdot}O{\cdot}NO \xrightarrow{h\nu} CF_3{\cdot}O{\cdot} \xrightarrow{SiO_2} COF_2 + SiF_4$$

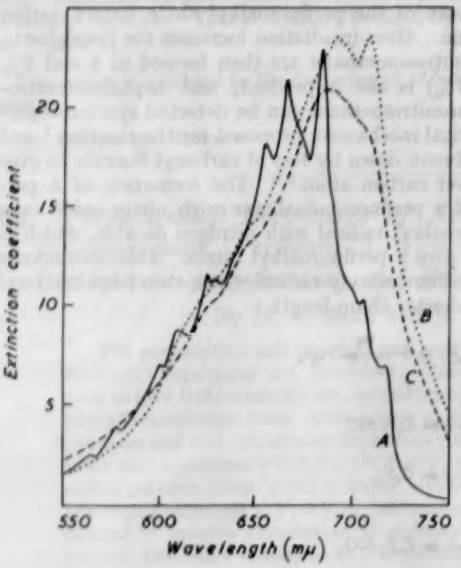
The dual rôle of mercury—removal of iodine to prevent radical recombination, and removal of dinitrogen tetroxide to prevent decomposition of the fluorocarbon chain—was emphasised earlier.[1,2]

[4] Jander and Haszeldine, *J.*, 1954, 912.
[5] Francis and Haszeldine, *J.*, 1955, 2151.
[6] Barr, Francis, and Haszeldine, *Nature*, 1956, **177**, 185.

The above scheme is supported by the photochemical reaction of heptafluoroiodopropane with dinitrogen tetroxide, which by reactions (iii), (iv), and (v) above yields heptafluoronitropropane (38%), pentafluoronitroethane (7%), and trifluoronitromethane (17%), and small amounts of trifluoronitrosomethane, as well as the main breakdown products carbonyl fluoride and silicon tetrafluoride:

$$CF_3\cdot[CF_2]_n\cdot \xrightarrow{NO_2} CF_3\cdot[CF_2]_n\cdot NO_2 + CF_3\cdot[CF_2]_{n-1}\cdot NO_2 + CF_3\cdot[CF_2]_{n-2}\cdot NO_2 + \ldots \text{ etc.}$$

It was earlier shown [4] that trifluoroiodomethane reacts with dinitrogen tetroxide to give trifluoronitromethane. The photochemical reaction of a perfluoroalkyl iodide with dinitrogen tetroxide is the simplest and quickest way of preparing the nitro-compounds on a small scale. The ready loss of carbonyl fluoride from a perfluoroalkoxy-radical parallels the decomposition of alkoxy-radicals into alkyl radicals and formaldehyde.[7]



Ultraviolet spectra of perfluoronitrosoalkanes.
A, $CF_3\cdot NO$. *B*, $C_2F_5\cdot NO$. *C*, $C_3F_7\cdot NO$.
(*All as vapour.*)

The ultraviolet spectrum of trifluoronitrosomethane shows appreciable fine structure in its long-wavelength band which has two main peaks at 665 and 683 mμ (see Figure and ref. 4 where comparison with other *C*-nitroso-compounds is made). Pentafluoronitrosoethane has a spectrum essentially similar in shape to that of trifluoronitrosomethane but with the two main peaks in the long-wavelength band shifted to the red by 20—25 mμ (692, 708 mμ) and with less fine structure (see Fig. and Table). Loss of fine structure is almost complete with heptafluoronitrosopropane which shows only a single broad peak (686 mμ) with several inflections (see Figure and Table).

The infrared spectrum of pentafluoronitrosoethane (D.M.S.*) shows the strong C–F stretching absorptions centred on 8·10 μ and the stretching vibration of the nitroso-group is clearly at 6·24 μ (cf. 6·25 μ in $CF_3\cdot NO$, ref. 4). The corresponding bands in heptafluoronitrosopropane (D.M.S.) are at 7·93, 8·07, and 6·23 μ. These N:O stretching vibrations should be compared with those of other *C*-, *O*-, and *N*-nitroso-compounds.[4, 6, 9]

Application of the method developed later for the oxidation of trifluoronitrosomethane

* Spectra thus marked have been offered for the D.M.S. scheme to Messrs. Butterworths, 88 Kingsway, London, W.C., to whom application should be made.

[7] See, for example, Adler, Pratt, and Gray, *Chem. and Ind.*, 1955, 1517.

to trifluoronitromethane, namely, heating with oxygen, now enables heptafluoronitropropane [1] to be prepared in 75—80% yield. The last compound, which has a Trouton's constant of 22·8, has an ultraviolet spectrum very similar to that of trifluoronitromethane

Ultraviolet spectra (vapour).

	$\lambda_{max.}$ (mμ)	ε	$\lambda_{min.}$ (mμ)	ε	$\lambda_{inf.}$ (mμ)	ε
(a) *C-Nitroso-compounds*						
$C_2F_5{\cdot}NO$	708	23·4	702	2·22	647	14·2
	692	23·6	—	—	625	11·4
$C_3F_7{\cdot}NO$	686	22·0	—	—	705	19·3
	—	—	—	—	695	20·5
	—	—	—	—	645	13·3
	—	—	—	—	612	7·7
(b) *C-Nitro-compounds*						
$CF_3{\cdot}NO_2$ [a]	279	11·0	239	2·0	—	—
$C_2F_5{\cdot}NO_2$	281	28·5	239	8·0	—	—
$C_3F_7{\cdot}NO_2$	282	36·0	236	3·8	—	—
(c) *Azoxy-compounds*						
$CF_3{\cdot}N^+(O^-){:}N{\cdot}CF_3$ [b]	303	7·4	280	6·0	—	—
	211	8000	—	—	—	—
$C_3F_7{\cdot}N^+(O^-){:}N{\cdot}C_3F_7$	305	17·0	285	14·6	—	—
	220	2740	—	—	—	—

[a] Taken from ref. 4. [b] Taken from ref. 8 where ε was printed as 17·4 instead of 7·4; the diagram in ref. 8 is correct.

and alkyl and halogenoalkyl nitro-compounds.[4,9,10] Its infrared spectrum (D.M.S.) shows the asymmetric stretching vibration at 6·16 μ and the symmetric stretching vibration at 7·79 μ or possibly at 8·09 μ [cf. $CF_3{\cdot}NO_2$ 6·13, 6·17 μ (doublet) and 7·64, 7·78, 7·87 μ (triplet), and see refs. 4 and 10 for a discussion of the spectra of such compounds]. Pentafluoronitrosoethane is similarly oxidised to pentafluoronitroethane in good yield; the asymmetric stretching vibration of the nitro-compound is at 6·15 μ, and the symmetric stretching vibration is at 7·85 or 8·05 μ.

Heptafluoronitrosopropane is decolorised when heated with active carbon at 150° and yields perfluoro-1 : 1′-azoxypropane, b. p. 94·5°, and heptafluoronitropropane :

$$3C_3F_7{\cdot}NO \longrightarrow C_3F_7{\cdot}N^+(O^-){:}N{\cdot}C_3F_7 + C_3F_7{\cdot}NO_2$$

The ultraviolet spectrum of perfluoroazoxypropane shows the characteristic weak long-wavelength and powerful short-wavelength maxima of azoxy-compounds. The asymmetric stretching vibration of the azoxy-group,[8] which electronically resembles a *C*-nitro-group, is well-defined in perfluoroazoxypropane (D.M.S.) at 6·39 μ (cf. 6·37 μ in hexafluoroazoxymethane). The symmetric stretching vibration is probably at 8·08 μ, but this assignment is less certain.

The reaction of heptafluoronitrosopropane with 10% aqueous base is interesting, since it yields pentafluoropropionic and trifluoroacetic acid as main products as well as fluoride, nitrite, and carbonate :

$$C_3F_7{\cdot}NO \xrightarrow[H_2O]{OH^-} C_2F_5{\cdot}CO_2H + CF_3{\cdot}CO_2H$$

Nucleophilic attack on the α-carbon atom of heptafluoronitrosopropane, possibly with formation of hyponitrous acid, readily explains the formation of pentafluoropropionic acid :

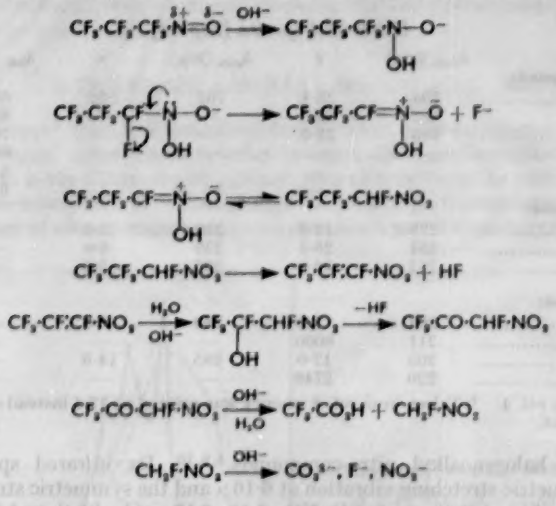
$$OH^- + C_3F_7{\cdot}N{:}O \longrightarrow C_2F_5{\cdot}CF_2{\cdot}OH + [HNO]$$

$$C_2F_5{\cdot}CF_2{\cdot}OH \xrightarrow{-HF} C_2F_5{\cdot}COF \longrightarrow C_2F_5{\cdot}CO_2H$$

$$[HNO] \longrightarrow H_2N_2O_2$$

[8] Jander and Haszeldine, *J.*, 1954, 919.
[9] Haszeldine and Jander, *J.*, 1954, 691; Haszeldine and Mattinson, *J.*, 1955, 4172; *Chem. and Ind.*, 1955, 81; Tarte, *Bull. Soc. chim. belges*, 1954, **63**, 525.
[10] Haszeldine, *J.*, 1953, 2525.

The following reaction scheme is suggested to explain the partial breakdown of the perfluoroalkyl group, which is normally extremely resistant to attack :



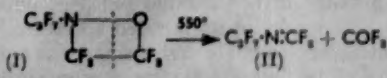
In this scheme nucleophilic attack on the nitrogen of the nitroso-group is followed by fluoride elimination in a manner similar to that postulated earlier for olefin formation from fluorocarbanions.[11] Rearrangement into hexafluoronitropropane is followed by elimination of hydrogen fluoride and base-catalysed hydration of the resultant olefin to give the fluoronitro-ketone. In an alkaline medium this ketone would undergo hydrolytic cleavage to trifluoroacetic acid (cf. $CF_3{\cdot}CO{\cdot}CF_3 \longrightarrow CF_3{\cdot}CO_2H$; $C_3F_7{\cdot}CO{\cdot}C_3F_7 \longrightarrow C_3F_7{\cdot}CO_2H$). Reaction schemes which involve formation of $C_3F_7^-$ or $C_2F_5^-$ are not likely, since such ions would yield C_3HF_7 or C_2HF_5, which are stable to base, as well as fluoro-olefins such as C_3F_6 and C_2F_4 by fluoride elimination, and such compounds were not detected. Aldehydes such as $C_2F_5{\cdot}CHO$ are similarly improbable intermediates, since they are known to be cleaved to formic acid and the corresponding hydrofluorocarbon (C_2HF_5) in an alkaline medium.

In marked contrast, heptafluoronitropropane is unchanged by prolonged contact with aqueous base at 120°. This suggests that initiation of the hydrolysis of heptafluoronitrosopropane is at the reactive nitroso-group and not at the α-carbon atom, and that the intermediate $C_2F_5{\cdot}CF_2{\cdot}N(OH){\cdot}O^-$ then decomposes either by nucleophilic attack on the α-carbon atom to give pentafluoropropionic acid as above, or by fluoride elimination with breakdown of the chain. The marked inertness of heptafluoronitropropane to aqueous alkali made re-investigation of the stability of trifluoronitromethane necessary, since the last compound was earlier considered to be stable to cold aqueous alkali [4] but slowly decomposed by prolonged contact.[8] Trifluoronitromethane is, in fact, stable to aqueous base at temperatures up to 100° and is thus very similar to heptafluoronitropropane.

Heptafluoronitrosopropane reacts in the dark with tetrafluoroethylene to give almost quantitatively a colourless liquid (b. p. 50·5°) and an involatile, clear, colourless, viscous oil. This reaction thus parallels that between trifluoronitrosomethane and tetrafluoroethylene.[2] Both products have empirical formula C_5NOF_{11}, *i.e.*, contain a 1 : 1 ratio of $C_3F_7{\cdot}NO$ to C_2F_4, and are unaffected by water or aqueous acid or alkali. Their infrared spectra fail to show the presence of groups such as N:O, NO_2, N:N·(O⁻), O·NO, O·NO_2, C:C, C:N, or N:N. The liquid, which has a molecular weight of 299, is perfluoro-2-*n*-propyl-1 : 2-oxazetidine (I), and proof of structure is afforded by its pyrolysis at 550° at

[11] Haszeldine, *Nature*, 1951, **168**, 1028; *J.*, 1952, 4259; *J.*, 1954, 4026 *et seq.*

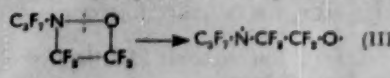
low pressure in absence of air to yield twice the original volume of gas, shown to consist of equimolar amounts of carbonyl fluoride and perfluoro(methylene-*n*-propylamine) (II) :



(I) (II)

The infrared spectrum (D.M.S.) of the oxazetidine (I) is very similar to that of perfluoro-2-methyl-1 : 2-oxazetidine [2] with C–F stretching absorptions centred on 8·0 μ and with a sharp band at 7·06 μ (cf. 7·05 μ in $CF_3{\cdot}N{\cdot}O{\cdot}CF_2{\cdot}CF_2$) which is possibly characteristic of this ring system. The structure of the perfluoro(methylenepropylamine) (II) follows from the method of preparation, from its infrared spectrum (D.M.S.), and from its hydrolysis described below.

It seems very probable that pyrolysis of the oxazetidine (I) occurs by initial fission of the N–O bond to give the diradical (III) which is also a perfluoroalkoxy-radical. As pointed out earlier (see also ref. 5), a perfluoroalkoxy-radical readily eliminates COF_2 :



(III)

$$C_3F_7{\cdot}\dot{N}{\cdot}CF_2{\cdot}CF_2{\cdot}O{\cdot} \longrightarrow COF_2 + C_3F_7{\cdot}\dot{N}{\cdot}CF_2{\cdot} \longrightarrow C_3F_7{\cdot}N{:}CF_2$$

Formation of perfluoro(methylenepropylamine) is thus readily visualised.

The infrared spectrum of the compound (II) shows the strong C:N stretching vibration at 5·51 μ with other strong bands at 9·85, 10·75, and 13·37 μ (cf. 5·53, 9·95, and 13·8 μ for $CF_3{\cdot}N{:}CF_2$, ref. 2).

It has recently been claimed [13] that pyrolysis of perfluoro-*tert.*-amines yields azomethines, *i.e.*, perfluoro(alkylenealkylamines), and one of the compounds reported was perfluoro(methylene-*n*-propylamine), obtained by pyrolysis of perfluoro-*tert.*-propylamine at 660—670°. It is unlikely that the material obtained by this route was in fact perfluoro(methylene-*n*-propylamine), since the b. p. reported (12·3°) for the unanalysed material is much lower than that which we observe (25·6°) for an analytically pure sample. The pyrolysis of a tertiary perfluoroamine, which has to be carried out under very stringent conditions in the presence of metal fluorides as catalysts, and must involve concurrent formation of fluorocarbons such as CF_4, C_2F_4, C_2F_6, C_3F_8, C_3F_6, C_4F_{10}, C_4F_8, etc., is unlikely to give good yields of perfluoro(methylenealkylamines), $CF_3{\cdot}[CF_2]_n{\cdot}N{:}CF_2$, to the exclusion of all other perfluoro(alkylenealkylamines) such as $CF_3{\cdot}[CF_2]_n{\cdot}CF_2{\cdot}N{:}CF{\cdot}[CF_2]_n{\cdot}CF_3$. Degradation from either end of a perfluoro(alkylenealkylamine) molecule is feasible :

$$CF_3{\cdot}[CF_2]_x{\cdot}CF_2{\cdot}N{:}CF{\cdot}[CF_2]_n{\cdot}CF_3 \longrightarrow CF_3{\cdot}[CF_2]_x{\cdot}CF_2{\cdot}N{:}CF{\cdot}[CF_2]_n{\cdot}CF_3$$

$$\text{or} \quad CF_3{\cdot}[CF_2]_x{\cdot}CF_2{\cdot}N{:}CF{\cdot}[CF_2]_n{\cdot}CF_3$$

where $x < n$.

Products such as $CF_3{\cdot}N{:}CF_2$, $C_2F_5{\cdot}N{:}CF_2$, $C_2F_5{\cdot}N{:}CF{\cdot}CF_3$, $CF_3{\cdot}N{:}CF{\cdot}CF_2{\cdot}CF_3$, $C_3F_7{\cdot}N{:}CF{\cdot}C_2F_5$, $C_3F_7{\cdot}N{:}CF{\cdot}CF_3$, $C_2F_5{\cdot}N{:}CF{\cdot}C_2F_5$, are thus to be expected when an amine such as $(C_3F_7)_3N$ is pyrolysed, and we therefore suggest that the product of b. p. 12·3° reported by Pearlson and Hals is either a mixture or the isomeric perfluoro(propylidenemethylamine) (IV) :

$$(C_3F_7)_3N \longrightarrow C_2F_5{\cdot}CF{:}N{\cdot}CF_3 \quad \text{(IV)}$$

The last compound, like perfluoro(methylene-*n*-propylamine) (II) (see below), would give pentafluoropropionic acid when treated with an excess of aqueous base :

cf. $CF_3{\cdot}CF_2{\cdot}CF_2{\cdot}N{:}CF_2 + 4H_2O \longrightarrow C_2F_5{\cdot}CO_2H + NH_4F + CO_2 + 3HF$

and $C_2F_5{\cdot}CF{:}N{\cdot}CF_3 \xrightarrow[OH^-]{H_2O} C_2F_5{\cdot}CF(OH){\cdot}NH{\cdot}CF_3 \longrightarrow C_2F_5{\cdot}CO{\cdot}NH{\cdot}CF_3 + HF$

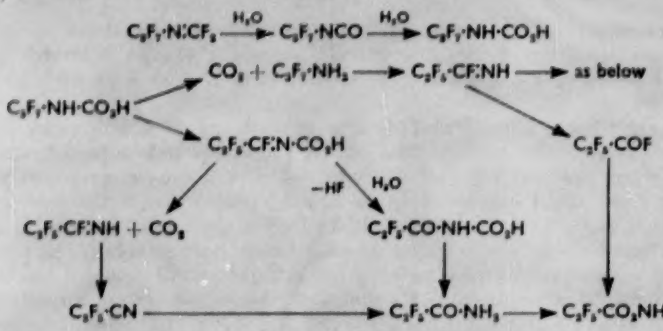
$$C_2F_5{\cdot}CO{\cdot}NH{\cdot}CF_3 \xrightarrow[H_2O]{OH^-} C_2F_5{\cdot}CO_2H + CO_2 + NH_4F + 2HF$$

[13] Pearlson and Hals, U.S.P. 2,643,267; *Chem. Abs.*, 1954, **48**, 6461.

That the pyrolysis product of perfluoro-2-*n*-propyl-1 : 2-oxazetidine is actually perfluoro-(methylene-*n*-propylamine) is shown by its reactions. When treated with an *excess* of water it is hydrolysed to, initially, carbon dioxide and pentafluoropropionitrile; the last compound can be identified by means of its infrared spectrum.[13] The nitrile is further hydrolysed to give pentafluoropropionamide and a smaller amount of ammonium pentafluoropropionate. Reaction of perfluoro(methylene-*n*-propylamine) with only a *limited amount* of water gave unchanged starting material and an almost quantitative yield of heptafluoro-*n*-propyl *iso*cyanate (b. p. 24·5°), spectroscopically identical with the material prepared from heptafluorobutyryl chloride as described in Part IV of this series (following paper). Heptafluoropropyl *iso*cyanate and pentafluoropropionitrile can also be isolated when perfluoro(methylene-*n*-propylamine) is treated with an excess of water, provided that the reaction time is short. The isolation of heptafluoropropyl *iso*cyanate clearly proves that a heptafluoropropyl group is present in perfluoro(methylene-*n*-propylamine) and that the material is not admixed with other perfluoro(alkylenealkylamines) such as $C_2F_5{\cdot}CF{:}N{\cdot}CF_3$ or $CF_3{\cdot}CF{:}N{\cdot}C_2F_5$. The difluoromethylene fluorine atoms are clearly very reactive :

$$C_3F_7{\cdot}N{:}CF_2 + H_2O \longrightarrow C_3F_7{\cdot}NCO + 2HF$$

The following reaction scheme is thus suggested for the hydrolysis of perfluoro(methylene-*n*-propylamine) with an *excess* of water :



Heptafluoropropyl *iso*cyanate is also formed when perfluoro(methylenepropylamine) is heated in glass at 160°, again revealing the reactivity of the difluoromethylene fluorine atoms :

$$C_3F_7{\cdot}N{:}CF_2 \xrightarrow{SiO_2} C_3F_7{\cdot}NCO + SiF_4$$

Perfluoro(methylenemethylamine) was shown to react [2] with a deficit of water to give unchanged starting material, silicon tetrafluoride, carbonyl fluoride, and an unknown volatile product showing infrared absorption at 4·4 μ (doublet); cyanogen fluoride and trifluoromethyl *iso*cyanate were considered to be possibilities. That the unknown product is actually trifluoromethyl *iso*cyanate produced by the reaction

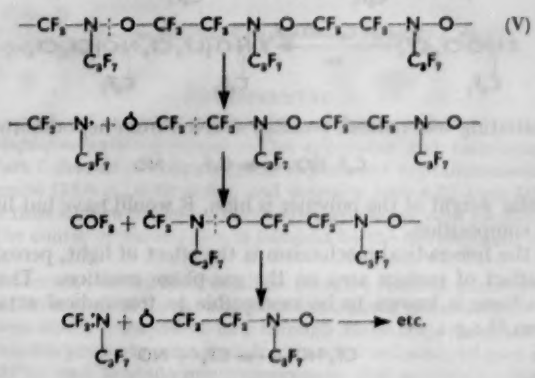
$$CF_3{\cdot}N{:}CF_2 + H_2O \longrightarrow CF_3{\cdot}N{:}C{:}O + 2HF$$

has now been shown by comparison of its infrared spectrum with that of a known specimen, whose synthesis will be described in Part IV. A reaction scheme for the hydrolysis of perfluoro(methylenemethylamine) involving trifluoromethyl *iso*cyanate is clearly now to be preferred over that involving initial C=N fission proposed earlier.[2] Trifluoromethyl *iso*cyanate is also produced when perfluoro(methylenemethylamine) is heated in silica, and there is thus a complete parallel between the reactions of $CF_3{\cdot}N{:}CF_2$ and $C_3F_7{\cdot}N{:}CF_2$.

The Polymer.—The clear, colourless, viscous oil obtained concurrently with perfluoro-2-*n*-propyl-1 : 2-oxazetidine is formed by copolymerisation of heptafluoronitrosopropane and

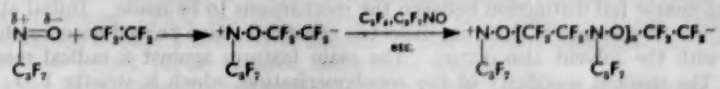
[13] See Haszeldine and Leedham, *J.*, 1953, 1548, for derivatives of pentafluoropropionic acid.

tetrafluoroethylene in a 1 : 1 ratio to give the polymer (V). Its infrared spectrum (D.M.S.) is similar to that of the oil obtained from trifluoronitrosomethane and tetrafluoroethylene, with C–F absorption at 8·10 and 8·80 μ and strong bands at 13·57 and 10·83 μ (cf. 13·45 and 10·93 μ, ref. 2). Proof of structure is given by pyrolysis of the oil to equimolar amounts of perfluoro(methylene-*n*-propylamine) and carbonyl fluoride quantitatively. This reaction probably proceeds by N–O fission followed by elimination of carbonyl fluoride from the resultant perfluoroalkoxy-radicals :



Reaction of heptafluoronitrosopropane with tetrafluoroethylene followed by pyrolysis of both the oxazetidine and the polymer produced thus gives perfluoro(methylene-*n*-propylamine) almost quantitatively.

Mechanism of Polymerisation.—The copolymerisation of a nitroso-compound and an olefin was noted for the first time with trifluoronitrosomethane and tetrafluoroethylene, and produces a novel copolymer.[14] Application of the ionic mechanism suggested for this copolymerisation [2,14] to the heptafluoronitrosopropane–tetrafluoroethylene case gives :

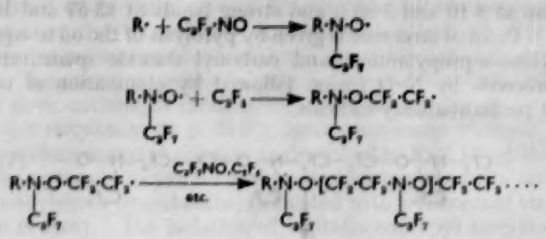


In support of such an ionic mechanism are : (*a*) The fact that the polymer : oxazetidine ratio varies markedly with reaction temperature; at 70° the ratio is 0·2 : 1, and at 20° is 5 : 1, with reaction essentially complete at both temperatures. A low temperature would favour a liquid-phase reaction and hence polymerisation to a polymer of high molecular weight; it is significant that the polymer formed at 70° is appreciably more mobile and has a lower molecular weight that than formed at 20°. (*b*) The formation of the oxazetidine from the intermediate $C_3F_7{\cdot}^+N{\cdot}O{\cdot}CF_2{\cdot}CF_2^-$ is readily visualised. (*c*) The formation of a 1 : 1 copolymer is as expected. Fluoro-olefins are known to be readily attacked by nucleophilic reagents (RO^-, R_2N^-, RS^-, etc.), and attack of the $-CF_2{\cdot}CF_2{\cdot}N(C_3F_7){\cdot}O^-$ ion on tetrafluoroethylene should occur readily.

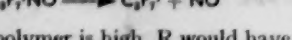
Further investigation of the influence of catalysts on the polymerisation has shown that a free-radical mechanism for the reaction must also be considered. A large increase in the surface area of the system produced by filling the reaction tube with glass wool caused no significant change either in rate or in the product ratio; this suggests that the reaction is not a heterogeneous surface reaction, or catalysed by glass. Exposure to ultraviolet radiation for a short period, or the addition of *tert.*-butyl peroxide to the reaction mixture, leads to a slightly increased rate of reaction, and the polymer : oxazetidine ratio is doubled. By contrast, reaction in the presence of quinol approximately halves the overall rate of

[14] Barr and Haszeldine, *Nature*, 1955, **175**, 991.

reaction and decreases the polymer : oxazetidine ratio eight-fold. All these observations suggest a free-radical reaction in the gas phase, *e.g.* :

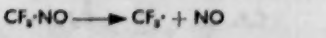


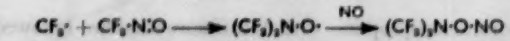
where R is an initiating free radical, possibly derived from heptafluoronitrosopropane :



Since the molecular weight of the polymer is high, R would have but little influence on the overall polymer composition.

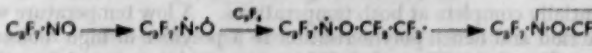
In favour of the free-radical mechanism is the effect of light, peroxide, and quinol and the absence of effect of surface area on the gas-phase reaction. The nitroso-group of a perfluoronitrosoalkane is known to be susceptible to free-radical attack which occurs at the nitrogen atom,[15] *e.g.* :





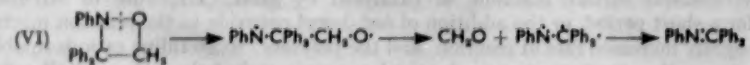
A free-radical mechanism does not involve the continual increase in charge separation as growth of polymer proceeds which is necessary in the ionic mechanism. It is also particularly suitable for the trifluoronitrosomethane–tetrafluoroethylene reaction;[2] here the reactants are in the gas phase, and increased surface area has negligible effect on reaction rate or product ratio.

The new evidence thus suggests a free-radical mechanism, but kinetic studies are clearly merited to enable full distinction between the mechanisms to be made. Initial attempts, involving use of solvents of differing dielectric constants, have proved unsuccessful, since reaction with the solvent also occurs. The main features against a radical mechanism are : (*a*) The marked specificity of the copolymerisation, which is strictly 1 : 1; this is unusual for a radical reaction. (*b*) The difficulty of explaining the formation of the oxazetidine without recourse to diradicals, *e.g.* :



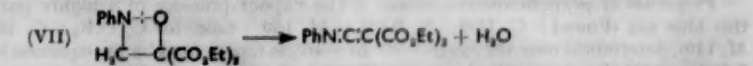
(*c*) The fact that reaction occurs readily even at −40° and gives a higher yield of polymer at the lower temperatures. Despite these points, the evidence at present available favours the radical mechanism for the formation of oxazetidine or polymer, or both.

Pyrolytic Decomposition of Other Oxazetidines.—The products obtained by pyrolysis of the oxazetidines prepared many years ago [16] from nitrosobenzene and 1 : 1-diphenylethylene diethyl methylenemalonate, or diphenylketen are somewhat unexpected at first sight. The idea of intermediate formation of an alkoxy-radical by initial N–O fission of the type postulated for the fluoro-oxazetidines makes the formation of these products somewhat easier to understand. Thus the oxazetidine (VI) would give an alkoxy-radical which could readily lose formaldehyde :

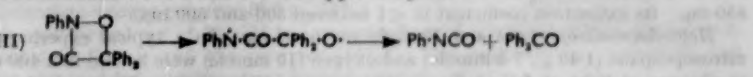


[15] Haszeldine and Mattinson, *Chem. and Ind.*, 1956, 81.
[16] Ingold and Weaver, *J.*, 1924, **125**, 1456; Staudinger and Jelagin, *Ber.*, 1911, **44**, 365.

whereas the oxazetidine (VII) would give an alkoxy-radical which could not lose formaldehyde; it apparently decomposes by loss of water:



The oxazetidine (VIII) would yield an alkoxy-radical which could lose neither formaldehyde nor water, and in this case C–CO bond fission apparently occurs:



Experimental

Reactions were carried out in sealed tubes unless otherwise stated.

Preparation of Heptafluoronitrosopropane.—The apparatus and technique were similar to those described in Part I (*loc. cit.*).* In a typical experiment heptafluoroiodopropane (35·3 g., 0·119 mole), nitric oxide (12·0 g., 0·40 mole), and mercury (400 ml.) were introduced into the 20 l. flask which was then shaken for 20—25 hr. whilst irradiated with an internal 12" Hanovia ultraviolet lamp. The course of the reaction is followed by the development of the intense blue colour.

Oxygen was then admitted to the flask until the pressure reached atmospheric, and the flask was set aside for 1 hr. to complete the oxidation of the unused nitric oxide. The volatile contents of the flask were slowly pumped (2 hr.) through three traps in series cooled by liquid oxygen. The condensable products were then fractionated *in vacuo*, to give unchanged heptafluoroiodopropane (57%) and heptafluoronitrosopropane (7·8 g., 76%). No difficulty is experienced in obtaining spectroscopically and analytically pure heptafluoronitrosopropane by this method provided that care is taken to exclude moisture, air, etc., to use clean apparatus, and to avoid over-irradiation.

The effects of over-irradiation are shown by the results of an earlier experiment in which heptafluoroiodopropane (2·43 g., 8·2 mmole), nitric oxide (0·51 g., 17 mmole), and mercury (75 ml.) were mechanically shaken in a 1 l. silica flask exposed to an external ultraviolet lamp (24 hr.). The products of six such experiments were combined and fractionated, to give heptafluoroiodopropane (traces only), heptafluoronitrosopropane (4·7 g., 23·6 mmole; 48%), perfluoro-*n*-hexane (2·25 g., 6·7 mmole; 27%), pentafluoronitrosoethane (2 mmole; 4%), trifluoronitrosomethane (1 mmole; 2%), heptafluoronitropropane, pentafluoronitroethane, trifluoronitromethane, carbon dioxide, and carbonyl fluoride. These products were identified by means of their molecular weight, vapour pressure, and infrared spectra.

Properties of Heptafluoronitrosopropane.—Heptafluoronitrosopropane is a blue gas which condenses to a purple liquid. The vapour pressure of a highly purified sample (Found: C, 18·1; N, 7·1%; *M*, 199. Calc. for C_3ONF_7: C, 18·1; N, 7·1%; *M*, 199), determined over the range −46° to −23°, is represented by the equation $\log_{10} p(\text{mm.}) = 7{\cdot}825 - 1303/T$, whence the b. p. is calculated to be −9·7°, the latent heat of vaporisation is 5960 cals./mole, and Trouton's constant is 22·6. The compound as prepared originally [1] had b. p. −12°. Banus [2] reported −14·5° but the high value of the Trouton constant (28) reported by this author reveals substantial impurity.

Heptafluoronitrosopropane shows maximum absorption in the ultraviolet only near 700 mμ (see Table) and its extinction coefficient is < 1 between 300 and 500 mμ. Heptafluoroiodopropane can be detected when present in trace amounts as impurity by the peak which appears at 270 mμ. Heptafluoronitrosopropane, like trifluoronitrosomethane,[3,4] has no maximum between 220 and 550 mμ.

Pentafluoronitrosoethane.—Pentafluoroiodoethane (2·46 g., 10·0 mmole), nitric oxide (0·90 g., 30 mmole), and mercury (100 ml.) were shaken in a 2 l. silica flask irradiated by an external Hanovia S250 ultraviolet lamp (20 hr.). The products were treated with oxygen to remove unused nitric oxide, then freed from the excess of oxygen by slow pumping through traps cooled with liquid oxygen. The condensable products were distilled *in vacuo*, to give pentafluoronitrosoethane (1·27 g., 8·5 mmole), trifluoronitrosomethane (0·015 g., 0·15 mmole), pentafluoroiodoethane (0·054 g., 0·22 mmole), and small amounts of carbon dioxide, carbonyl fluoride, and

* [*Note added*, 15.3.56.] An overriding advantage of this method of preparation of perfluoronitrosoalkanes is that relatively large amounts of the pure nitroso-compound can be obtained in a short time without the use of large silica apparatus and without the repeated filling of small silica tubes.

silicon tetrafluoride. The yield of pentafluoronitrosoethane is 87% calculated on the iodo-compound used (98%).

Properties of pentafluoronitrosoethane. The vapour pressure of a highly pure specimen of this blue gas (Found: C, 15·9; N, 9·6%; *M*, 150. Calc. for C_2ONF_5: C, 16·1; N, 9·4%; *M*, 149), determined over the range −80° to −46°, is represented by the equation $\log_{10} p(\text{mm.}) = 7{\cdot}690 - 1094/T$, whence the b. p. is calculated as −45·7°, the latent heat of vaporisation is 5005 cals./mole, and Trouton's constant is 22·0. Haszeldine [1] gives b. p. −42°. The compound shows maximum absorption in the ultraviolet near 700 mμ, and no maximum between 220 and 550 mμ; its extinction coefficient is <1 between 300 and 500 mμ.

Heptafluoronitropropane and Pentafluoronitroethane.—In a typical experiment heptafluoronitrosopropane (1·49 g., 7·5 mmole) and oxygen (10 mmole) were heated in a 400 ml. Pyrex tube in absence of light at 70° (4 days); the gas was then green. The products condensable by liquid oxygen were shaken with mercury in a Carius tube to remove dinitrogen tetroxide, then distilled *in vacuo* to give heptafluoronitropropane (0·82 g., 78%) (Found: C, 16·9; N, 6·7%; *M*, 216. Calc. for $C_3O_2NF_7$: C, 16·8; N, 6·5%; *M*, 215), heptafluoronitrosopropane (0·52 g., 35%), and carbon dioxide. The vapour pressure equation of the nitro-compound, determined over the range −26° to 23°, is $\log_{10} p(\text{mm.}) = 7{\cdot}865 - 1491/T$, whence the calculated b. p. is 26·0°, the latent heat of vaporisation is 6820 cals./mole, and Trouton's constant is 22·8. Haszeldine [1] gives b. p. 26°.

Pentafluoronitrosoethane was similarly converted into pentafluoronitroethane [1] in good yield.

Photochemical Reaction of Heptafluoroiodopropane with Dinitrogen Tetroxide.—The iodo-compound (0·500 g., 1·7 mmole) and dinitrogen tetroxide (0·370 g., 8·0 mmole) in a 50 ml. sealed tube were exposed to ultraviolet light (24 hr.). The excess of dinitrogen tetroxide was removed by treatment with mercury, and fractionation of the volatile products *in vacuo* gave heptafluoronitropropane (0·138 g., 38%), pentafluoronitroethane (0·018 g., 7%), trifluoronitromethane (0·033 g., 17%), carbonyl fluoride, carbon dioxide, and silicon tetrafluoride. The products were identified by infrared spectroscopic examination. Small amounts of trifluoronitrosomethane were detected spectroscopically in the most volatile fraction which was blue.

*Perfluoro-*1 : 1′*-azoxypropane.*—Heptafluoronitrosopropane (2·5 g., 12·5 mmole) and active carbon (5 g.; activated by heating at 150° *in vacuo* for 2 hr.) were sealed in a 200 ml. tube in absence of air, then heated at 70° in the dark (5 days). The contents of two such tubes were combined and fractionated, to give heptafluoronitropropane (identified spectroscopically) and *perfluoro-*1 : 1′*-azoxypropane* (1·3 g., 3·4 mmole; 27% based on heptafluoronitrosopropane). The last product was dried over calcium oxide (0·2 g.), then fractionated *in vacuo*, to give the pure compound, b. p. 94·5° (isoteniscope) (Found: C, 19·0; N, 7·1%; *M*, 378. $C_6ON_2F_{14}$ requires C, 18·9; N, 7·3%; *M*, 382).

Hydrolyses.—(a) *Heptafluoronitrosopropane.* The nitroso-compound (0·99 g., 0·5 mmole) and 10% aqueous sodium hydroxide (5 ml.), sealed in a 50 ml. Pyrex tube in absence of air and shaken mechanically at room temperature in the dark until the blue colour disappeared (12 hr.), gave a solution which contained nitrite, fluoride, and carbonate ions. Neutralisation of the aqueous solution by nitric acid was followed by treatment with 20-vol. hydrogen peroxide (0·5 ml.) and silver nitrate (1 g.). Extraction by moist ether of the solid obtained by evaporation of the aqueous solution to dryness gave silver pentafluoropropionate (0·051 g., 0·22 mmole; 44%) and silver trifluoroacetate (0·034 g., 0·14 mmole; 28%), identified and analysed spectroscopically. A control experiment showed that 80% of a perfluoro-acid was recovered as silver salt by this procedure, and if corrected by this factor the above yields become 55 and 35% respectively.

(b) *Heptafluoronitropropane.* The nitro-compound (0·077 g., 0·37 mmole) and 20% aqueous sodium hydroxide (5 ml.) were sealed in a 20 ml. Pyrex tube in absence of air and heated at 120° for 30 hr. The tube was attacked and a gelatinous precipitate of silicate was apparent. Fractionation of the volatile products gave unchanged heptafluoronitropropane (0·076 g., 0·355 mmole; 99%) (Found: *M*, 212. Calc. for $C_3O_2NF_7$: *M*, 215).

(c) *Trifluoronitromethane.* The nitro-compound (0·101 g., 0·88 mmole) and 10% aqueous sodium hydroxide (1 ml.) failed to react at 70° (20 hr.), and trifluoronitromethane (0·100 g., 99%) (Found: *M*, 115. Calc. for CO_2NF_3: *M*, 115) was recovered.

Reaction of Heptafluoronitrosopropane with Tetrafluoroethylene.—In a typical experiment, heptafluoronitrosopropane (1·99 g., 10 mmole) and tetrafluoroethylene (1·05 g., 10·5 mmole) were sealed in a 250 ml. Pyrex tube in absence of air and heated at 80° in absence of light until the gas was nearly colourless (4 days). The volatile products were fractionated *in vacuo*, to give unchanged reactants (5%) and *perfluoro-*2-n-*propyl-*1 : 2*-oxazetidine* (1·80 g., 6·0 mmole;

63%), b. p. 50·5° (isoteniscope) (Found: C, 20·2; N, 4·7%; *M*, 302. C_5ONF_{11} requires C, 20·0; N, 4·7%; *M*, 299). The reaction vessel also contained an involatile colourless viscous oil which was a 1 : 1 *copolymer* of heptafluoronitrosopropane and tetrafluoroethylene [Found: C, 20·0; N, 5·0%. $(C_5ONF_{11})_n$ requires C, 20·0; N, 4·7%].

Effect of Conditions on the Heptafluoronitrosopropane–Tetrafluoroethylene Reaction.—(a) *Temperature.* Heptafluoronitrosopropane (0·495 g., 2·49 mmole) and tetrafluoroethylene (0·260 g., 2·6 mmole), sealed in a 40 ml. Pyrex tube in absence of air and kept in the dark at 20° (4 days), gave unchanged reactants (10%), perfluoro-2-propyl-1 : 2-oxazetidine (0·105 g., 0·35 mmole; 15%), and the colourless viscous polymer (0·5 g., 75%).

A parallel reaction carried out at 70° (24 hr.) gave unchanged reactants (10%), perfluoro-2-propyl-1 : 2-oxazetidine (75%), and the polymer (15%). The polymer was noticeably less viscous than that obtained by experiments at lower temperatures.

(b) *Catalysts.* In a series of experiments carried out under controlled conditions, heptafluoronitrosopropane (0·615 g., 3·1 mmole) and tetrafluoroethylene (0·310 g., 3·1 mmole) were sealed in a 50 ml. Pyrex tube containing the catalyst under investigation. The tube was warmed rapidly to room temperature, and placed in an oven at 30° for 24 hr. Both reactants were thus in the vapour phase. Reaction was then stopped by cooling in liquid oxygen, and the volatile products were fractionated rapidly *in vacuo*. Unchanged reactants and the oxazetidine were identified by their b. p. and molecular weight. The weight of polymer produced was obtained by weighing the reaction tube, then removing the polymer by pyrolysis, after which the tube was reweighed.

Results, which are reproducible to 2%, are given in the annexed Table.

	Control	Glass wool [1]	U.V. light [2]	$Bu^t_2O_2$ [3]	Quinol [3]
Reaction (%) after 24 hr.	52	50	56	62	26
Yield of oxazetidine based on reactants used	37	38	25	25	83
Ratio, polymer/oxazetidine	1·7	1·6	3·0	3·0	0·2

[1] Reaction tube packed with Pyrex glass wool. [2] Pyrex reaction tube exposed to radiation from a Hanovia ultraviolet lamp for 10 min. [3] 7% by weight of total reactants.

Pyrolysis of the Heptafluoronitrosopropane–Tetrafluoroethylene Copolymer.—The polymer (0·350 g.) in a silica tube was heated in absence of air at 450—500° at 10^{-2} mm., the technique described earlier [2] being used, and the pyrolysate was condensed in a trap cooled by liquid oxygen. Fractionation of the products gave unchanged polymer, carbonyl fluoride (0·046 g., 0·7 mmole) (Found: *M*, 66. Calc. for COF_2: *M*, 66), and *perfluoro(methylene-n-propylamine)* (1·63 g., 0·7 mmole) (Found: C, 20·7; N, 5·8%; *M*, 234. C_4NF_9 requires C, 20·6; N, 6·0%; *M*, 233). The conversion was 60%, *i.e.*, essentially quantitative after allowance for the recovered polymer. The vapour pressure of perfluoro(methylene-n-propylamine), determined over the range −23° and 18°, is given by the equation $\log_{10} p(\text{mm.}) = 7{\cdot}827 - 1478/T$, whence the b. p. is calculated as 25·6°, the latent heat of vaporisation is 6760 cals./mole and Trouton's constant is 22·5.

Pyrolysis of Perfluoro-2-n-propyl-1 : 2-oxazetidine.—The oxazetidine (0·33 g., 1·1 mmole) was passed at 5 mm. pressure and in absence of air through a silica tube of 15 mm. internal diameter, heated at 550—600° over a length of 30 cm. (15 min.). There was no reaction at 450°. The products were fractionated *in vacuo*, to give carbonyl fluoride (0·074 g., 1·12 mmole) (Found: *M*, 67. Calc. for COF_2: *M*, 66) and perfluoro(methylene-*n*-propylamine) (0·245 g., 1·05 mmole; 96%). The infrared spectrum of the last compound was identical with that of the compound obtained by pyrolysis of the polymer.

Reactions of Perfluoro(methylene-n-propylamine).—(a) *With an excess of water.* The compound (0·10 g., 0·44 mmole) and water (0·5 g., 28 mmole), sealed in a 5 ml. Pyrex tube in absence of air, reacted with effervescence as the tube warmed to room temperature and two liquid phases could be seen. After 5 min. the tube suddenly became warm and crystals appeared; there was apparently no further change on storage. Fractionation of the volatile products gave carbon dioxide (0·13 mmole) and pentafluoropropionitrile (0·20 mmole, 45%), both identified by means of their infrared spectra. The crystalline material was spectroscopically identified as pentafluoropropionamide (*ca.* 0·12 mmole, 27%), contaminated by ammonium pentafluoropropionate (*ca.* 0·03 mmole, 7%).

In a second experiment, perfluoro(methylenepropylamine) (0·47 mmole) and water (28 mmole), sealed in a 5 ml. tube in absence of air, reacted as above to give two liquid phases. The volatile products were at once fractionated, to give unchanged perfluoro(methylenepropylamine) (0·19 mmole, 41%), heptafluoropropyl *iso*cyanate (0·05 mmole, 17%), carbon dioxide (0·11 mmole), and pentafluoropropionitrile (0·11 mmole, 40%).

(b) *With a deficit of water.* Perfluoro(methylenepropylamine) (0·091 g., 0·39 mmole) was sealed in absence of air in a 5 ml. tube which was attached by rubber tubing to a 3 l. flask which was then evacuated. Water (0·029 g., 1·6 mmole) was introduced into the flask, and in this volume was all in the vapour phase. The tip of the tube containing the perfluoro(methylenepropylamine) was then broken so that this compound entered the reaction flask and mixed rapidly with water vapour. After 32 hr. the contents of the flask were fractionated *in vacuo*, to give water, perfluoro(methylenepropylamine) (0·052 g., 0·22 mmole), and heptafluoropropyl *iso*cyanate (0·034 g., 0·16 mmole); the products were identified and analysed by means of their molecular weight and infrared spectra. The yield of heptafluoropropyl *iso*cyanate calculated on the basis of perfluoro(methylenepropylamine) used (44%) is quantitative within the experimental error. The preparation and infrared spectrum of heptafluoropropyl *iso*cyanate are discussed in the following paper.

(c) *With glass.* Perfluoro(methylenepropylamine) (0·072 g., 0·31 mmole) and powdered Pyrex glass (0·2 g.) were heated at 160° in a 5 ml. Pyrex tube in absence of air or moisture (27 hr.), to give unchanged perfluoro(methylenepropylamine), silicon tetrafluoride, and heptafluoropropyl *iso*cyanate (*ca.* 20%), all identified by means of their infrared spectra.

One of us (D. A. B.) is indebted to Imperial Chemical Industries Limited for a maintenance grant.

UNIVERSITY CHEMICAL LABORATORY, CAMBRIDGE. [*Received, January 7th*, 1956.]

---

664. *Perfluoroalkyl Derivatives of Nitrogen. Part IV.* The Synthesis, Properties and Infrared Spectra of Perfluoroalkyl* iso*Cyanates and Carbamates.*

By D. A. BARR and R. N. HASZELDINE.

Trifluoromethyl and heptafluoropropyl *iso*cyanate have been synthesised (*a*) by the Curtius reaction, (*b*) by controlled hydrolysis of perfluoro(methylenealkylamines), and (*c*) by reaction of perfluoro(methylenealkylamines) with silica. Perfluoroalkyl carbamates are prepared from the *iso*cyanates by reaction with an alcohol, or by reaction of the alcohol with the perfluoro(methylenealkylamine). Reactions of the perfluoroalkyl *iso*cyanates and carbamates which lead to partial breakdown of the perfluoroalkyl group have been examined. Assignments are made for the $\nu_{a(NCO)}$ and $\nu_{s(NCO)}$ vibrations of the *iso*cyanate group which can thus be distinguished spectroscopically from the nitrile group. Assignments are also made for the C:O, N–H stretching, and N–H deformation vibrations in *N*-alkyl-, *N*-aryl-, and *N*-perfluoroalkylcarbamates.

THE Hofmann degradation of amide to amine:[1]

$$R{\cdot}CO{\cdot}NH_2 + NaOBr \longrightarrow R{\cdot}NH_2 + CO_2 + NaBr$$

is said to fail when R is a perfluoroalkyl group such as CF_3, C_2F_5, or C_3F_7.[2,3] Trifluoroacetamide was considered to yield hexafluoroethane,[2] and the higher homologues a perfluoroalkyl bromide.[3] Consideration of the reactions of fluorine compounds and of the mechanism of the Hofmann reaction made these results irreconcilable to us. We have therefore re-examined the issue and wish to clarify and correct some of the earlier results.

The present communication is concerned with the synthesis and reactions of perfluoroalkyl *iso*cyanates and carbamates, since these compounds are the intermediates in the normal Hofmann degradation of amide to amine. Our interpretation of the Hofmann reaction with perfluoroalkyl amides is to be reported in Part V of this series, and correlated with the Curtius reaction with perfluoroalkanecarboxylic acids and with the results of Hofmann

* Part III, preceding paper.

[1] Hofmann, *Ber.*, 1881, **14**, 2725.
[2] Gryszkiewicz-Trochimowski, Sporzynski, and Wnuk, *Rec. Trav. chim.*, 1947, **66**, 426.
[3] Husted and Kohlhase, *J. Amer. Chem. Soc.*, 1954, **76**, 5141.

and Curtius reactions with derivatives of carboxylic acids containing polar groups other than perfluoroalkyl groups.

Perfluoroalkyl iso*Cyanates.*—Trifluoromethyl *iso*cyanate and heptafluoropropyl *iso*cyanate were prepared by three routes: (*a*) the Curtius reaction with a perfluoroacyl halide:

$$R_F{\cdot}COCl \longrightarrow R_F{\cdot}CON_3 \longrightarrow R_F{\cdot}NCO + N_2$$

(*b*) controlled hydrolysis of the perfluoro(methylenealkylamine):

$$R_F{\cdot}N{:}CF_2 + H_2O \longrightarrow R_F{\cdot}NCO + 2HF$$

and (*c*) reaction of the perfluoro(methylenealkylamine) with silica at 160—200°:

$$R_F{\cdot}N{:}CF_2 \longrightarrow R_F{\cdot}NCO + SiF$$

This last method is not of great practical value but illustrates the reactivity of the difluoromethylene-fluorine atoms.

The synthesis of trifluoromethyl and heptafluoro-*n*-propyl *iso*cyanate by a conventional Curtius reaction gave but little difficulty; the perfluoroacyl azides decompose smoothly but more slowly than their alkyl analogues. The preparation of heptafluoropropyl *iso*cyanate has been described in a patent,[4] but it was there predicted that trifluoroacetyl azide would be dangerously explosive and that it could not be employed to make trifluoromethyl *iso*cyanate; we find no marked difference between the trifluoromethyl and the heptafluoropropyl compound. It has been suggested several times [3,4,5] that there is an inherent difference between trifluoromethyl compounds on the one hand, and pentafluoroethyl, heptafluoropropyl, etc., compounds on the other which is " a change in kind and not in degree of reactivity " [4] so that there is " a transition point in the physical and chemical properties in the series ".[5] Thus the compounds CF_3–Z (Z = CON_3, $CO{\cdot}NH_2$, or CO_2H) have been reported as showing large chemical differences from the compounds C_2F_5–Z and C_3F_7–Z, and this has led to a belief that many trifluoromethyl derivatives cannot be made even though the pentafluoroethyl or heptafluoropropyl derivatives are known. This belief in a change in kind is founded upon wrong evidence, *e.g.*, (*a*) the apparent failure to prepare trifluoromethyl *iso*cyanate and (*b*) the reported products of the Hofmann reaction with trifluoroacetamide. There are sometimes minor differences in physical properties from those predicted for trifluoromethyl compounds, *e.g.*, the increment in boiling point between a CF_3 and a C_2F_5 derivative is often different from what it is between a C_2F_5 and a C_3F_7 derivative; such differences are of minor import, however, and are reflected in slight or moderate changes in the degree of reactivity of the compounds, *e.g.*, trifluoroiodomethane yields a Grignard derivative less readily than heptafluoroiodopropane,[6] but the difference in reactivity is never such that the heptafluoropropyl compound can exist whilst the trifluoromethyl compound cannot.

Use of carefully controlled conditions enables perfluoro(methylene-*n*-propylamine) to be hydrolysed to heptafluoropropyl *iso*cyanate in almost theoretical yield,[7,8] and application of similar conditions to perfluoro(methylenemethylamine) would doubtless give yields of trifluoromethyl *iso*cyanate higher than reported here (50%).

The perfluoroalkyl *iso*cyanates are considerably more volatile than their unsubstituted analogues (cf. $CF_3{\cdot}NCO$, b. p. −36°; $CH_3{\cdot}NCO$, b. p. 44°), an effect often found in fluorine chemistry.

N-*Perfluoroalkylcarbamates.*—Perfluoroalkyl *iso*cyanates react in normal fashion with water, aqueous alkali, or ethanol; that the products expected by analogy with alkyl *iso*cyanate reactions are not always isolated is caused not by the failure of the –NCO group to react in conventional manner, but by the instability of the $-CF_2{\cdot}NH-$ group when present in a medium of high dielectric constant. If this principle is borne in mind there

[4] Ahlbrecht and Husted, U.S.P. 2,617,817; *Chem. Abs.*, 1953, **47**, 8774.
[5] Husted and Ahlbrecht, *J. Amer. Chem. Soc.*, 1953, **75**, 1605.
[6] Haszeldine, *J.*, 1952, 3423; 1953, 1748; 1954, 1273.
[7] Barr and Haszeldine, *J.*, 1955, 1881.
[8] *Idem*, Part II, *J.*, 1955, 2532; Part III, preceding paper.

is nothing anomalous in the *iso*cyanate reactions, and clear predictions for other reactions can be made.

Heptafluoropropyl *iso*cyanate reacts with water, to give heptafluoropropylcarbamic acid (I) which is decarboxylated to heptafluoropropylamine (II); the last product cannot be isolated as such from an aqueous medium, since rapid decomposition and elimination of hydrogen fluoride yields pentafluoropropionitrile (III), which can be isolated. Further hydrolysis takes place if the reaction mixture is kept, particularly in presence of the acid produced by fluoride liberation, giving pentafluoropropionamide (IV) and thence ammonium pentafluoropropionate (V), both of which have been detected. Decomposition of the $-CF_2\cdot NH-$ system is probably sufficiently rapid to prevent its reaction with heptafluoropropyl *iso*cyanate to give a disubstituted urea, *e.g.*, $(C_3F_7\cdot NH)_2CO$, but even if formed this would be unstable in an aqueous medium and would yield pentafluoro-propionitrile, -propionamide, and, ultimately, -propionate.

Aqueous sodium hydroxide similarly converts heptafluoropropyl *iso*cyanate into sodium pentafluoropropionate.

The perfluoroalkyl *iso*cyanates react normally with anhydrous alcohols to give alkyl *N*-perfluoroalkylcarbamates (urethanes), *e.g.*, ethyl *N*-heptafluoro-*n*-propylcarbamate (VI). The carbamates have also been synthesised by reaction of perfluoro(methylenealkylamines) with a *limited* amount of ethanol, *e.g.*,

$$CF_3\cdot N{:}CF_2 \xrightarrow{EtOH} CF_3\cdot NH\cdot CO_2Et$$

The hydrogen fluoride produced reacts with perfluoro(methylenemethylamine), to give bistrifluoromethylamine, thus showing that the high temperatures used earlier [8] for the preparation of this amine are not essential.

The *iso*cyanate is probably immediately formed as intermediate when a perfluoro(methylenealkylamine) reacts with an alcohol, although addition of ethanol to the N:C bond followed by loss of hydrogen fluoride and ultimate formation of ethyl ether constitutes a less likely alternative route to the *iso*cyanate, *e.g.*,

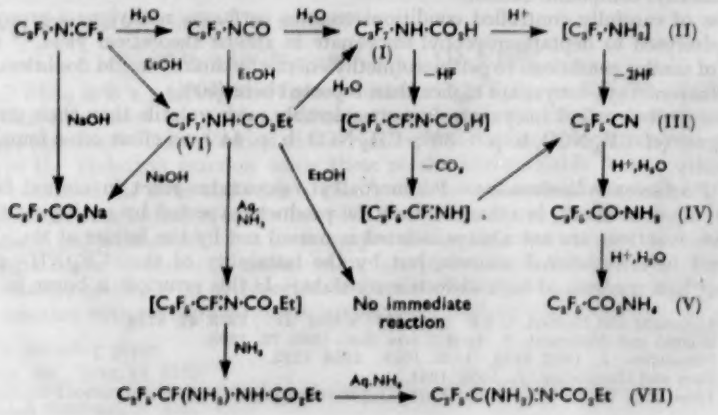
$$(a)\quad C_3F_7\cdot N{:}CF_2 \longrightarrow C_3F_7\cdot NCO + 2HF \longrightarrow C_3F_7\cdot NH\cdot CO_2Et$$

or

$$(b)\quad C_3F_7\cdot N{:}CF_2 \longrightarrow C_3F_7\cdot NH\cdot CF_2\cdot OEt \longrightarrow C_3F_7\cdot N{:}CF\cdot OEt \longrightarrow C_3F_7\cdot NH\cdot CF(OEt)_2$$

$$C_3F_7\cdot NH\cdot CF(OEt)_2 \longrightarrow C_3F_7\cdot N{:}C(OEt)_2 \longrightarrow C_3F_7\cdot N{:}C{:}O + Et_2O$$

This formation of ethyl perfluoroalkylcarbamates almost quantitatively from perfluoro-(methylenealkylamines) is in accord with the formation of the *iso*cyanates by controlled aqueous hydrolysis, and shows that N=C fission is not the initial step (cf. Part I) of the hydrolysis or alcoholysis of perfluoro(methylenealkylamines); the reactivity of the difluoromethylene-fluorine atoms [7] is the key factor.



The *N*-perfluoroalkylcarbamates are low-melting solids which are readily soluble, and stable, in an excess of ethanol at room temperature, thus showing that the $-CF_2\cdot NH-$ system can exist in a polar solvent provided that acid or base is absent. They decompose slowly when kept for several hours in alcoholic solution; under these conditions perfluoro-(methylenemethylamine) reacted with an excess of anhydrous methanol to give dimethyl ether, dimethyl carbonate, and ammonium fluoride.[7] The carbamates are insoluble in cold water and react with it only after several minutes or when shaken. Ethyl heptafluoropropylcarbamate, when allowed to react slowly with water, yields a solid which is probably *N*-heptafluoropropylcarbamic acid (I). Aqueous base rapidly converts ethyl heptafluoropropylcarbamate into sodium pentafluoropropionate.

Ahlbrecht and Husted [4] described the reaction of heptafluoropropyl *iso*cyanate with methanol and *o*-bromophenol to give urethanes (carbamates); they also noted that aqueous ammonia and methyl heptafluoropropylcarbamate gave a solid, m. p. 104—106°, believed to have formula (VII). The formation of a compound of this type is best visualised as involving elimination of hydrogen fluoride, followed by nucleophilic addition of ammonia and loss of a second molecule of hydrogen fluoride as shown. A similar process would account for the formation of the solid, m. p. 156—158°, believed [4] to be $C_2F_5\cdot C(NH_2){:}N\cdot CO\cdot NH_2$, on reaction of heptafluoropropyl *iso*cyanate with aqueous ammonia.

Infrared Spectra of Perfluoroalkyl iso*Cyanates and Carbamates.*—The interaction of the pseudo-symmetrical vibrations $\nu_{C=O}$ and $\nu_{C\equiv N}$ in cyanic acid [9] and in methyl *iso*cyanate [10] is considered to give one very strong anti-symmetrical absorption $\nu_{a(NCO)}$ at *ca.* 4·4 μ and a weak symmetrical absorption $\nu_{s(NCO)}$ at *ca.* 7·4 μ. Davison [11] examined eight *iso*cyanates for these stretching vibrations and showed that $\nu_{a(NCO)}$ gives a characteristic absorption at 4·41 μ. Nitriles absorb in the same region, but at slightly longer wavelength (4·44 μ). Assignment of the $\nu_{s(NCO)}$ vibration must only be tentative in the 7·4 μ region, since bands associated with methyl and methylene deformations cause ambiguity, although a band at 7·26 μ in methyl *iso*cyanate was so assigned.[10] Unambiguous assignment of $\nu_{s(NCO)}$ usually cannot be made, however, and the possible value of this vibration to distinguish *iso*cyanates from nitriles is thus lost.

The infrared spectra of the perfluoroalkyl *iso*cyanates $CF_3\cdot NCO$ and $C_2F_7\cdot NCO$ are of interest in this connection, since there is no question of interference by C–H absorptions. Trifluoromethyl *iso*cyanate shows a doublet for $\nu_{a(NCO)}$ like cyanic acid and at much the same wavelength (see Table). Heptafluoropropyl *iso*cyanate shows only a single peak at 4·37 μ. The perfluoroalkyl *iso*cyanates thus show a small but definite shift to shorter wavelength for $\nu_{a(NCO)}$ relative to alkyl or aryl *iso*cyanates; such shifts are often observed on introduction of fluorine into a molecule.[12]

Heptafluoropropyl *iso*cyanate shows two bands, at 6·80 and 7·40 μ, which might be assigned to $\nu_{s(NCO)}$, but since trifluoromethyl *iso*cyanate shows a strong band at 6·84 μ and only a weak band at 7·50 μ, preference is given to the 6·80 or 6·84 μ band. The strength of this band is noteworthy, since it is considerably more powerful than in alkyl *iso*cyanates. A somewhat similar change in extinction coefficient was observed [13] with bis(perfluoroalkyl)-amines such as $(CF_3)_2NH$, where the N–H deformation vibration appears as a strong band at 6·65 μ; in unsubstituted dialkylamines the N–H deformation vibration is very weak or absent.

Perfluoroalkanenitriles show the C:N stretching vibration at 4·41 μ, *i.e.*, at slightly longer wavelength than the stretching vibration of the –NCO group. Distinction between perfluoroalkyl *iso*cyanates and related nitriles thus cannot be made with certainty on grounds of band position alone, but clear distinction is possible if the intensity of absorption is also considered, since the C:N vibration is much weaker than the –NCO vibration; the presence of a strong band at 6·8 μ confirms a perfluoroalkyl *iso*cyanate structure.

[9] Herzberg and Reid, *Discuss. Faraday Soc.*, 1950, **9**, 92.
[10] Eyster and Gillette, *J. Chem. Phys.*, 1940, **8**, 369.
[11] Davison, *J.*, 1953, 3712.
[12] Haszeldine, *Nature*, 1951, **168**, 1028.
[13] Barr and Haszeldine, *J.*, 1955, 4169.

The infrared spectra of perfluoroalkylcarbamates are interesting (see Table). These compounds are hydrogen-bonded in the liquid or solid state, since the C:O and N–H stretching vibrations of ethyl *N*-heptafluoropropylcarbamate, for example, move markedly to shorter wavelength when the compound is in the vapour phase. The spectrum of the

Infrared spectra.

isoCyanates.

		ν_a(NCO)	ν_s(NCO)
CF_3·NCO (D.M.S.) [a]	v	4·33, 4·40 doublet	6·84
C_2F_5·NCO (D.M.S.)	v	4·37	6·80
Ph·NCO	v	4·40	[c]
" (D.M.S.) ...	l	4·40	[c]
HNCO [b]	v	4·37, 4·42 doublet	7·54
CH_3·NCO [10]	v	4·48 [b]	7·26
CH_2·$[CH_2]_{17}$·NCO [11]	N	4·44	[c]
$[CH_2]_6(NCO)_2$ [11]	N	4·44	[c]

Nitriles.

		ν_{CEN}			ν_{CEN}
CF_3·CN ...	v	4·40	CCl_3·CN...	l	4·45
C_2F_5·CN...	v	4·41	CH_2Cl·CN	l	4·44
C_3F_7·CN...	v	4·41	—	—	—

Carbamates (urethanes).

		N–H stretch.	N–H deform.	C:O
CF_3·NH·CO_2Et ...	N	3·07	6·50	5·79
C_3F_7·NH·CO_2Et ...	l	2·90, 3·07	6·51	5·73
	v	2·91	6·67	5·62
CH_3·NH·CO_2Et ...	l	3·00	6·49	5·88
	s	2·98, 2·88	6·49, 6·60	5·79
CH_3Ph·NH·CO_2Et	N		[c]	5·92
	s	[c]	[c]	5·74
Ph·NH·CO_2Et	N	3·04	6·54	5·81, 5·88, 5·74
	s	2·91	6·57	5·74
NH_2·CO_2Et	N	[c]	[c]	5·92
	s	[c]	[c]	5·77
CH_3·N(NO)·CO_2Et	l	—	—	5·71
	s	—	—	5·71
C_3F_7·NH·CO_2H ...	N	3·14	6·49	5·62

[a] Spectra thus marked have been offered for the D.M.S. scheme to Messrs. Butterworths, 88 Kingsway, London, W.C., to whom application should be made.
v = vapour, l = liquid film, N = Nujol mull, s = solution in CCl_4. [c] Assignment uncertain, [b] Accuracy doubtful. [d] Not examined, or assignment doubtful.

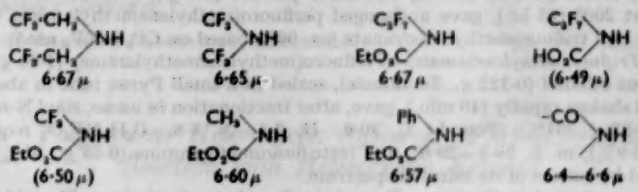
liquid carbamate shows both free (2·90 μ) and bonded (3·07 μ) N–H vibrations. The C:O stretching vibration is at a distinctly longer wavelength than that for esters of perfluoroalkanecarboxylic acids (5·55—5·60 μ) such as ethyl heptafluorobutyrate, but at an appreciably shorter wavelength than that for ethyl *N*-methylcarbamate.

The infrared spectra of ethyl *N*-methyl-, *N*-benzyl-, and *N*-phenyl-carbamate also reveal strong hydrogen bonding in the liquid or solid (see Table). Ethyl *N*-methylcarbamate shows a shift in the N–H stretching vibration of 0·12 μ, and in the C:O stretching vibration of 0·09 μ when dissolved in carbon tetrachloride. Ethyl *N*-benzylcarbamate shows a similar shift in the C:O vibration. The spectrum of ethyl *N*-phenylcarbamate shows the bonded carbonyl group as a doublet at 5·81 and 5·88 μ, and the " free " carbonyl group is present as a weak side band at 5·74 μ; only one strong band, at 5·74 μ, appears when the compound is dissolved in carbon tetrachloride. Ethyl carbamate also shows strong hydrogen bonding. That the shifts in the N–H and C:O vibrations reported above are caused by intermolecular hydrogen bonding of the –N–H····O=C– type is supported by the infrared spectrum of *N*-methyl-*N*-nitrosourethane which shows unbonded C:O absorption at 5·71 μ both as a liquid and in solution.

The strong band at 6·50 μ in the spectrum of ethyl *N*-trifluoromethylcarbamate, and a similar band in the spectrum of ethyl *N*-heptafluoropropylcarbamate as liquid (6·51 μ) or vapour (6·67 μ) is assigned to the N–H deformation vibration. Ethyl *N*-methylcarbamate, ethyl *N*-phenylcarbamate, and heptafluoropropylcarbamic acid also show bands in this region and a similar assignment is made; the benzene-ring absorption is at 6·26 μ. Several bands appear in the spectra of solutions of ethyl *N*-benzylcarbamate and ethyl carbamate in the 6·3—6·6 μ region; the strongest of these (6·45 μ) is probably the N–H deformation vibration, but this assignment is less certain than for the examples discussed above.

The N–H deformation vibration is not normally visible in secondary alkylamines, but it is markedly increased in intensity when the amine contains fluorine, *e.g.*, in $(CF_3·CH_2)_2NH$ and $(CF_3)_2NH$.[13] It appears to be a general phenomenon that attachment of an electronegative group to nitrogen enhances the intensity of the N–H deformation band. The annexed compounds all contain at least one strongly electronegative group attached to the

N–H group, and all show a band near 6·65 μ when the compound is in the vapour phase or solution (*i.e.*, non-bonded N–H) or at 6·5—6·6 μ for a bonded N–H group (values given in parentheses). It will be noted that the N–H deformation vibration is at a longer wavelength when the N–H group is "free" than when it is hydrogen-bonded (*e.g.*, $C_3F_7{\cdot}NH{\cdot}CO_2Et$, see Table); this shift is the opposite of that found for the N–H stretching vibration.



The only other assignment which is plausible for the band appearing near 6·65 μ is the stretching vibration of the C–N bond; this would imply partial double bond character of the C–N link. The situation is similar to that prevailing for the amide I and amide II bands of substituted amides (see ref. 14 for a discussion) except that the possibility of keto-enol tautomerism can be eliminated. The absence of a strong band near 6·65 μ in the spectra [7,8,13] of compounds such as $(CF_2{\cdot}CH_2)_2N{\cdot}NO$, $(CF_2{\cdot}CH_2)_2N{\cdot}NO_2$, $CF_2{\cdot}NO_2$, $C_3F_7{\cdot}NO_2$, $CF_2{\cdot}NO$, $C_3F_7{\cdot}NO$, $CF_2{\cdot}N{:}N^+(O^-){\cdot}CF_2$, or $(CF_3)_2N{\cdot}O{\cdot}NO$, however, suggests that the 6·65 μ band in the compounds $(CF_2{\cdot}CH_2)_2NH$, $(CF_3)_2NH$, $CF_3{\cdot}NH{\cdot}CO_2Et$, and $C_3F_7{\cdot}NH{\cdot}CO_2Et$ is best assigned to the N–H deformation vibration.

Experimental

See earlier Parts for details of the preparation of starting materials and the techniques used.

Trifluoromethyl iso*Cyanate.*—(a) ***From trifluoroacetyl chloride.*** Trifluoroacetyl chloride (0·920 g., 7·0 mmole), dry sodium azide (1·0 g., 15 mmole), and anhydrous mesitylene (40 ml.) were sealed in a 200 ml. Pyrex tube, then shaken vigorously for 30 min. in a boiling-water bath; shaking was continued after removal of the tube from the bath until it reached room temperature. Nitrogen was detected when the reaction vessel was opened, and fractionation of the volatile products gave trifluoroacetyl chloride (0·340 g., 2·6 mmole; 37%) and some trifluoromethyl *iso*cyanate. The remainder of the products were transferred from the Pyrex tube to a flask fitted with reflux condenser leading to a trap cooled in liquid oxygen. The flask was then slowly heated to 165° during which process bubbles of gas were evolved from the solid present, and material collected in the cold trap; the flask was finally kept at 165° for 2 hr. Fractionation of the products of the cold trap gave a mixture (1·4 mmole) of trifluoromethyl *iso*cyanate (80%) and trifluoroacetyl chloride (20%), analysed by molecular-weight and infrared-spectral determinations. The combined impure trifluoromethyl *iso*cyanate was kept in a 10 ml. tube with dry silver cyanide (0·5 g.) for 7 days at 20°; under these conditions trifluoroacetyl halides are converted into trifluoroacetyl cyanide dimer (W. C. Francis, unpublished results). Refractionation then gave ***trifluoromethyl isocyanate*** (0·125 g., 1·13 mmole; 26%) (Found: C, 21·6; N, 12·8%; *M*, 111. C_2ONF_3 requires C, 21·6; N, 12·6%; *M*, 111). The low yield is attributed to handling losses on the scale used rather than to any inherent difficulty in the reaction, and there is no doubt that the yield could be improved substantially. The vapour pressure of trifluoromethyl *iso*cyanate determined over the range −78° to −45° is given by $\log_{10} p(\text{mm.}) = 7{\cdot}838 - 1176/T$, whence the b. p. is calculated as −36·0°, the latent heat of vaporisation is 5380 cals./mole, and Trouton's constant is 22·7.

(b) ***From perfluoro(methylenemethylamine) by reaction with water.*** Perfluoro(methylenemethylamine) (0·067 g., 0·50 mmole) in a sealed 5 ml. ampoule was inserted in a 3 l. flask which was evacuated. Water vapour (0·037 g., 2·0 mmole) was then admitted to the flask, and the tip of the ampoule was broken. This rapid mixing of the reactants in the vapour phase caused immediate reaction. After 24 hr. at 20° fractionation of the volatile products *in vacuo* gave unchanged perfluoro(methylenemethylamine) (0·32 mmole, 64%) identified by means of its

[14] Randall, Fowler, Fuson, and Dangl, "Infrared Determination of Organic Structures," van Nostrand Co., New York, 1949.

infrared spectrum, silicon tetrafluoride, a small amount of carbon dioxide, and trifluoromethyl *iso*cyanate (*ca.* 50% based on $CF_3{\cdot}N{:}CF_2$ used). The last compound was identified by means of the characteristic bands in its infrared spectrum at 4·33, 4·40 μ (doublet), 6·83, 8·30, 8·62, 8·66 (doublet), and 14·10 μ.

(c) *From perfluoro(methylenemethylamine) by reaction with silica.* Perfluoro(methylenemethylamine) (0·050 g., 0·38 mmole) and silica powder (0·5 g.), sealed in a 5 ml. silica tube and heated at 200° (75 hr.), gave unchanged perfluoro(methylenemethylamine) (90%), silicon tetrafluoride, and trifluoromethyl *iso*cyanate (*ca.* 90% based on $CF_3{\cdot}N{:}CF_2$ used).

Ethyl N-Trifluoromethylcarbamate.—Perfluoro(methylenemethylamine) (1·00 g., 7·5 mmole) and anhydrous ethanol (0·322 g., 7·0 mmole), sealed in a small Pyrex tube in absence of air or moisture and shaken rapidly (40 min.), gave, after fractionation *in vacuo*, *ethyl N-trifluoromethylcarbamate* (0·37 g., 31%) (Found: C, 30·6; H, 3·6; N, 8·8. $C_4H_6NF_3O_2$ requires C, 30·6; H, 3·8; N, 8·9%), m. p. 28·5—29·0°, and bistrifluoromethylamine (0·58 g., 51%). The latter was identified by means of its infrared spectrum.

Heptafluoro-n-propyl isoCyanate.—From heptafluorobutyryl chloride. The chloride (1·65 g., 7·1 mmole), anhydrous toluene (7 ml.), and dry sodium azide (1·2 g., 18 mmole) were sealed in a 200 ml. Pyrex tube in absence of air, then kept at −22° (10 min.) before being allowed to warm slowly to 20° (2 hr.). The tube was shaken overnight at room temperature, then heated at 110° (2 hr.). Fractionation of the volatile products *in vacuo* gave heptafluoro-*n*-propyl *iso*cyanate (1·22 g., 5·8 mmole; 82%), b. p. 24·5° (isoteniscope) (Found: C, 22·8; N, 6·4%; *M*, 212. Calc. for C_4ONF_7: C, 22·7; N, 6·6%; *M*, 211). Ahlbrecht and Husted [4] report b. p. 25°/740 mm. See also Part III.[5]

Ethyl N-Heptafluoro-n-propylcarbamate.—Heptafluoro-*n*-propyl *iso*cyanate (0·45 g., 2·14 mmole) and anhydrous ethanol (0·098 g., 2·1 mmole) were sealed in a 30 ml. Pyrex tube in absence of air or moisture, then set aside at room temperature for 2 hr. Only traces of the reactants remained, and distillation of the liquid product gave only *ethyl N-heptafluoro-n-propylcarbamate* (0·49 g., 91%) (Found: C, 28·5; H, 2·3; N, 5·4. $C_6H_6O_2NF_7$ requires C, 28·0; H, 2·3; N, 5·5%), b. p. 55—58°/9 mm., m. p. (sealed tube) 10—11°.

The carbamate (0·056 g., 0·22 mmole) was unchanged when kept in anhydrous ethanol (2 ml.) in absence of air or moisture at 20° for 16 hr. and was recovered in 80% yield.

Hydrolysis of Ethyl N-Heptafluoro-n-propylcarbamate.—(a) *By water.* The carbamate (0·032 g., 0·125 mmole) in a sealed fragile glass tube was inserted into a larger tube containing water (1 ml., 55 mmole). The tube was then sealed and shaken vigorously to break the inner tube and allow rapid mixing. The globules of the carbamate slowly disappeared without evolution of gas, and white crystals appeared (30 min.). The crystals, which were separated and dried *in vacuo* over phosphoric anhydride, are believed to be of *N*-heptafluoropropylcarbamic acid (0·015 g., 52%), since infrared spectroscopic examination showed a fluoro-acid carbonyl band at 5·62 μ (cf. $CF_3{\cdot}CO_2H$ 5·56 μ), N–H stretching absorption at 3·14 μ, and N–H deformation vibration at 6·49 μ. The spectroscopic examination also showed that the solid was not pentafluoropropionamide or ethyl heptafluoropropylcarbamate.

(b) *By aqueous alkali.* The carbamate (0·080 g., 0·31 mmole) and 10% aqueous sodium hydroxide (1 ml.) were shaken in a small sealed tube. The globules of the carbamate disappeared rapidly and when, after 3 hr., the tube was opened, ammonia was detected as gaseous product. The aqueous solution was neutralised (dilute nitric acid), then evaporated to dryness with silver nitrate (1 g.). Extraction with ether, followed by evaporation to dryness, yielded silver pentafluoropropionate (0·070 g., 84%), identified by means of its infrared spectrum. A blank experiment showed that about 80% of sodium pentafluoropropionate can be recovered from aqueous solution as silver salt by this procedure, and if allowance is made for this, the yield of sodium pentafluoropropionate is quantitative within experimental error.

Reaction of Perfluoro(methylene-n-propylamine) with Ethanol.—(a) *With an excess of perfluoro(methylenepropylamine).* Perfluoro(methylene-*n*-propylamine) (0·345 g., 1·48 mmole) and anhydrous ethanol (0·061 g., 1·33 mmole) were sealed in a 5 ml. Pyrex tube, shaken, and warmed rapidly to room temperature. After 15 min. the volatile material present was entirely unchanged perfluoro(methylene-*n*-propylamine) (0·100 g., 0·43 mmole; 39%). Fractionation of the liquid product gave only ethyl *N*-heptafluoro-*n*-propylcarbamate [0·150 g., 0·58 mmole; 58% based on perfluoro(methylenepropylamine) used], identified by means of its infrared spectrum.

(b) *With an excess of ethanol.* Perfluoro(methylenepropylamine) (0·253 g., 1·08 mmole) and anhydrous ethanol (4 ml., 70 mmole) were sealed in a 5 ml. tube and set aside at room temperature for 1·5 hr. Ethyl carbonate, ammonium fluoride, and ethyl heptafluoropropylcarbamate

were identified in the distilled liquid products by means of their infrared spectra; carbon dioxide was not detected.

Spectra.—Spectra were recorded by a Perkin-Elmer Model 21 spectrophotometer with rock-salt optics. A 10 cm. gas cell was used for vapour spectra, and sealed cells for liquid samples.

One of us (D. A. B.) is indebted to Imperial Chemical Industries Limited, Plastics Division, for a maintenance allowance.

UNIVERSITY CHEMICAL LABORATORY, CAMBRIDGE. [*Received, March 20th*, 1956.]

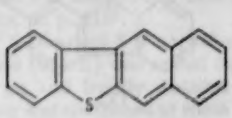
---

665. *Polynuclear Heterocyclic Systems. Part X.* The Elbs Reaction with Heterocyclic Ketones.*

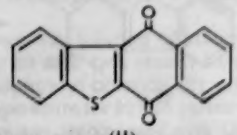
By G. M. BADGER and B. J. CHRISTIE.

Pyrolysis of 3-*o*-toluoylthionaphthen gives 9-thia-1 : 2-benzofluorene (X) and not the expected 9-thia-2 : 3-benzofluorene (I). A mechanism for this rearrangement has been suggested.

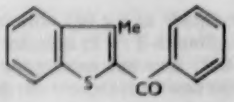
9-THIA-2 : 3-BENZOFLUORENE (I) was obtained by Mayer [1] by reduction of the quinone (II), prepared from phthalic anhydride and thionaphthen. The same quinone was obtained from thioisatin and ω-bromoacetophenone in sodium hydroxide solution. Werner [2] also prepared 9-thia-2 : 3-benzofluorene, albeit in only 5—8% yield, by pyrolysis of 2-benzoyl-3-methylthionaphthen (III), and its isolation was cited as a proof that the Friedel–Crafts acylation of 3-methylthionaphthen involves the 2-position. Other polynuclear heterocyclic compounds have also been prepared by the Elbs reaction; but synthesis involving



(I)



(II)



(III)

cyclisation into a five-membered hetero-ring has been achieved only very rarely, and in poor yield.[3,4] 9-Thia-2 : 3-benzofluorene was required by us for spectroscopic examination and it was thought of interest to attempt to prepare it by pyrolysis of 3-*o*-toluoylthionaphthen (IV).

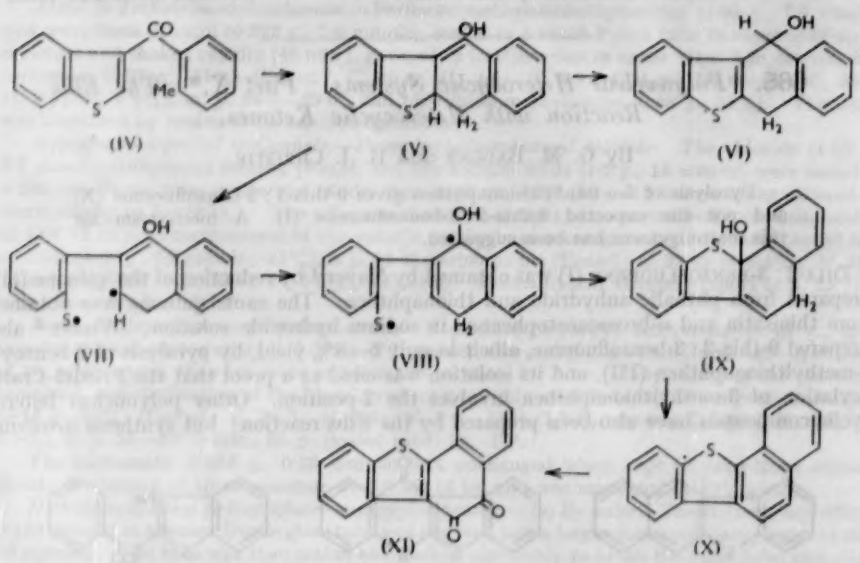
This ketone was prepared in good yield from thionaphthen and *o*-toluoyl chloride with stannic chloride, and was pyrolysed at 340—360°. Chromatography of the crude product gave a small quantity of the *p*-quinone (II), presumably the result of oxidation on the surface of the alumina; but the major product was unexpectedly 9-thia-1 : 2-benzofluorene (X), as proved by its m. p. and absorption spectrum,[5] and by oxidation with chromic acid to a red *o*-quinone (XI), which formed a quinoxaline derivative with *o*-phenylenediamine.

Although the evidence is still incomplete, a reasonable mechanism has been proposed for the Elbs reaction,[3,6] and the formation of the intermediate (V) seems very probable. In a " normal " Elbs reaction, this would be expected to undergo prototropic rearrangement to the alcohol (VI) and then dehydration to 9-thia-2 : 3-benzofluorene (I). A little of the corresponding *p*-quinone (II) has certainly been isolated following chromatography of the product, but this may have been formed directly by oxidation (on the alumina) of

* Part IX, *J.*, 1956, 122.

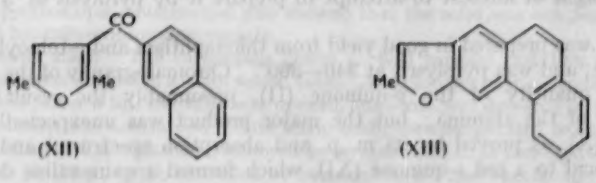
[1] Mayer, *Annalen*, 1931, **488**, 259.
[2] Werner, *Rec. Trav. chim.*, 1949, **68**, 520.
[3] Fieser, *Org. Reactions*, 1942, **1**, 129.
[4] de Clercq, *Ind. chim. belge*, 1955, **20**, 157.
[5] Kruber and Grigoleit, *Chem. Ber.*, 1954, **87**, 1895.
[6] Badger and Pettit, *J.*, 1953, 2774.

the intermediate (V). The present reaction appears, however, to be " abnormal " in that the major product is the angular compound (X); experiment has shown that it is not formed by heating 9-thia-2 : 3-benzofluorene (I) at 390° for 3 hours, and the rearrangement must therefore occur at an intermediate stage in the synthesis. It is suggested that the carbon–sulphur bond in the intermediate (V) may be ruptured at the temperature of the pyrolysis, the resulting radical (VII) rearranging to (VIII) and finally (IX), dehydration of which would lead to the observed product (X).



It must be concluded that the structure of the product of an Elbs reaction can be accepted only with caution.

An attempt has also been made to prepare the methylfuranophenanthrene (XIII) by pyrolysis of the ketone (XII). The ketone was prepared from 2 : 5-dimethylfuran,



2-naphthoyl chloride, and stannic chloride, though the yield was low, and longer reaction times and higher temperatures led to resins. The pyrolysis was attempted under various conditions but, although water was evolved, no crystalline material could be obtained. The instability of the furan nucleus at high temperatures may preclude the use of the Elbs reaction with such compounds.

Experimental

3-o-*Toluoylthionaphthen.*—Stannic chloride (22 g.) in thiophen-free benzene (100 c.c.) was added during 30 min., at room temperature, to a stirred solution of thionaphthen (10 g.) and *o*-toluoyl chloride (11·5 g.) in thiophen-free benzene (150 c.c.). The mixture was refluxed for 4 hr., then poured on ice and hydrochloric acid. The benzene layer was washed with 10% hydrochloric acid, water, 10% sodium hydroxide solution, and water, then dried (Na_2SO_4) and

evaporated. The resulting 3-*o*-*toluoylthionaphthen* (17 g., 90%) recrystallised from ethanol as colourless plates, m. p. 94° (Found: C, 76·6; H, 4·8; S, 12·85; O, 6·4. $C_{16}H_{12}OS$ requires C, 76·2; H, 4·8; S, 12·7; O, 6·3%). The 2 : 4-*dinitrophenylhydrazone* crystallised from chloroform–ethanol as orange needles, m. p. 261° (Found: C, 61·1; H, 3·9; N, 12·7; S, 7·3. $C_{22}H_{16}O_4N_4S$ requires C, 61·1; H, 3·7; N, 13·0; S, 7·4%).

9-*Thia*-1 : 2-*benzofluorene*.—The above ketone (10 g.) was heated at 340—360° for 3 hr. The cooled product was chromatographed in benzene on alumina. Elution with benzene gave two fractions: (i) light brown crystals (3·5 g.) and (ii) brown-yellow needles (0·4 g.). Recrystallisation of the second fraction from benzene gave 9-thia-2 : 3-benzofluorene-1 : 4-quinone as bright yellow needles, m. p. 215°, not depressed by admixture with an authentic specimen prepared by Mayer's method.[1] Fraction (i), repeatedly crystallised from hexane (charcoal), gave 9-thia-1 : 2-benzofluorene as colourless plates, m. p. 185° (Found: C, 82·2; H, 4·6; S, 13·8. Calc. for $C_{16}H_{10}S$: C, 82·0; H, 4·3; S, 13·7%). Its m. p. and ultraviolet absorption spectrum were identical with those recorded by Kruber and Grigoleit.[5] The 2 : 4 : 7-*trinitrofluorenone complex* crystallised from benzene as orange needles, m. p. 234° (sealed capillary) (Found: C, 63·9; H, 2·95; N, 7·5. $C_{29}H_{11}O_7N_3S$ requires C, 63·4; H, 2·75; N, 7·65%).

9-*Thia*-1 : 2-*benzofluorene*-3 : 4-*quinone*.—A mixture of 9-thia-1 : 2-benzofluorene (0·5 g.), chromic acid (0·5 g.), acetic acid (15 c.c.), and water (10 c.c.) was refluxed for 15 min., then poured into water. After recrystallisation from benzene the *quinone* formed red needles, m. p. 217° (Found: S, 12·1; O, 11·8. $C_{16}H_8O_2S$ requires S, 12·1; O, 12·1%). The *quinoxaline derivative*, prepared by use of *o*-phenylenediamine in acetic acid–ethanol, recrystallised from benzene as yellow needles, m. p. 230° (sealed capillary) (Found: C, 78·95; H, 3·7. $C_{22}H_{12}N_2S$ requires C, 78·5; H, 3·6%).

Attempted Isomerisation of 9-*Thia*-2 : 3-*benzofluorene*.—An authentic specimen of 9-thia-2 : 3-benzofluorene (0·5 g.) was heated at 390° for 3 hours. A small amount of isomerisation would be difficult to detect; so, after cooling, the product was oxidised with chromic acid (0·5 g.) in acetic acid, and the resulting quinone chromatographed in benzene on alumina. No red *o*-quinone was observed, 9-thia-2 : 3-benzofluorene-1 : 4-quinone (0·3 g.) being isolated as yellow needles, m. p. 215°.

2 : 5-*Dimethyl*-3-2′-*naphthoylfuran*.—A solution of stannic chloride (30 g.) in thiophen-free benzene (50 c.c.) was added during 30 min. to a stirred ice-cold solution of 2 : 5-dimethylfuran (10·5 g.) and freshly distilled 2-naphthoyl chloride (21 g.) in anhydrous benzene (200 c.c.). Stirring was continued at room temperature for 30 min., after which the temperature was raised to 35° for 15 min. The cooled mixture was decomposed with dilute hydrochloric acid and extracted with chloroform, and the organic layer washed with 10% hydrochloric acid, water, 10% aqueous sodium hydroxide, and water, then dried (Na_2SO_4) and evaporated. After distillation (b. p. 137—140°/0·02 mm.) and recrystallisation from hexane, the *furan* (11 g., 40%) formed colourless needles, m. p. 76° (Found: C, 81·75; H, 5·8; O, 13·0. $C_{17}H_{14}O_2$ requires C, 81·6; H, 5·6; O, 12·8%). The 2 : 4-*dinitrophenylhydrazone* crystallised from chloroform–hexane in orange needles, m. p. 211—212° (Found: C, 64·0; H, 4·3; O, 18·6. $C_{23}H_{18}O_5N_4$ requires C, 64·2; H, 4·2; O, 18·6%).

Microanalyses were carried out by the C.S.I.R.O. Microanalytical Laboratory, Melbourne.

UNIVERSITY OF ADELAIDE, SOUTH AUSTRALIA. [*Received, February 7th, 1956.*]

666. *Polynuclear Heterocyclic Systems. Part XI.* Absorption Spectra of Compounds containing Five-membered Rings.*

By G. M. Badger and B. J. Christie.

The absorption spectra of the polycyclic compounds derived from the five-membered heterocyclic systems have been found to resemble those of the related benzenoid hydrocarbons. Three main regions of absorption can generally be resolved, and the chief differences seem to be: (i) that the absorption of the heterocyclic compounds (particularly of the group I bands) is shifted to shorter wavelengths, and (ii) that the group III bands are more intense than those given by the hydrocarbons. The spectra of dicyclic and tricyclic furan systems resemble those of the related hydrocarbons rather less closely.

The absorption spectra of some *S*-oxides and -dioxides have also been compared with those of the parent thiophen derivatives.

The absorption spectra of the aromatic aza-compounds (pyridine, quinoline, etc.) have been shown to resemble very closely those of the corresponding hydrocarbons,[1] and with certain reservations the spectra of the parent hydrocarbons can be used for structural identification in the aza-series. The polycyclic compounds derived from the five-membered heterocyclic systems furan, pyrrole, and thiophen have, however, received considerably less attention. As part of a comprehensive study of the aromatic character of such heterocyclic compounds, their absorption spectra have been systematically compared with those of the analogous benzenoid systems.

In furan, pyrrole, and thiophen, each hetero-atom has two electrons available for conjugation with the four electrons contributed by the four annular carbon atoms. If the electronegativity of the hetero-atom is very high, its $2p$ orbital is "contracted" relatively to the carbon $2p$ orbitals, so that little conjugation occurs.[2] This is the case with furan. Nitrogen is less electronegative than oxygen, so that pyrrole occupies an intermediate position. With thiophen, however, the electronegativity of the hetero-atom is the same as that of carbon. Moreover, it seems that the two electrons from the sulphur atom may occupy two pd_2 hybrid orbitals, and the resulting conjugation with the carbon π-electrons is thereby greatly facilitated.[3] In all these cases, therefore, the electronic structures are similar to that which occurs in benzene, and it is not surprising that these heterocyclic compounds resemble benzene to some extent.

Benzene shows three main regions of ultraviolet-light absorption: intense absorption, with a maximum at 179 mμ, in the far ultraviolet region (group I band); a region of lower intensity around 200 mμ (group II bands); and of low intensity around 230—260 mμ (group III bands). Thiophen has three similar regions of absorption; but the spectra of furan and pyrrole are much less similar.[2] For example, no group III absorption has been detected with pyrrole. On the other hand, 1-methylpyrrole does show absorption in the 225—260 mμ region, and this is thought to be due to a reduction in the electronegativity of the nitrogen atom by methyl substitution.[2]

A comparable situation has now been found to exist with the bicyclic compounds (Fig. 1). Only thionaphthen (II; X = S) shows three well-defined absorption bands, with maxima at 227 (log ε 4·45), 257 (log ε 3·74), and 288 mμ (log ε 3·31), and the spectrum is similar to that of naphthalene (I). It is of interest that the high extinction coefficient of the group III band of thionaphthen is much greater than in the case of the hydrocarbon. Only two main regions of absorption can be resolved with indole (II; X = NH). The first, with a maximum at 219 mμ, probably corresponds to the group I band of naphthalene. The maximum at 288 mμ probably corresponds to the group III region, so the group

* Part X, preceding paper.

[1] Badger, Pearce, and Pettit, *J.*, 1951, 3199.
[2] Walsh, *Quart. Rev.*, 1948, **2**, 73.
[3] Longuet-Higgins, *Trans. Faraday Soc.*, 1949, **45**, 173.

II region cannot be clearly distinguished. Only two regions have been resolved for benzofuran (II; X = O). In this case the group I region seems to be beyond the range of the present instrument. The maximum at 244 mμ probably corresponds to the group II region of naphthalene, and that at 281 mμ to the group III region. These heterocyclic compounds all commence absorption at shorter wavelengths than naphthalene.

The spectra of the tricyclic compounds (IV) resemble that of the related hydrocarbon (III) rather more closely (Fig. 2). Phenanthrene [4] has three main regions of absorption at 250, 270—290, and 310—345 mμ, and both dibenzothiophen and carbazole have very similar absorption curves, except that the group I bands are shifted to somewhat shorter wavelengths. Thus dibenzothiophen has three main absorption regions at 235, 275—285, and 305—330 mμ, and carbazole absorbs around 240, 280—295, and 320—340 mμ. In both cases the intensity of the long-wavelength absorption (group III) is considerably greater for the heterocyclic compounds than for phenanthrene. As with the bicyclic

FIG. 1. FIG. 2.

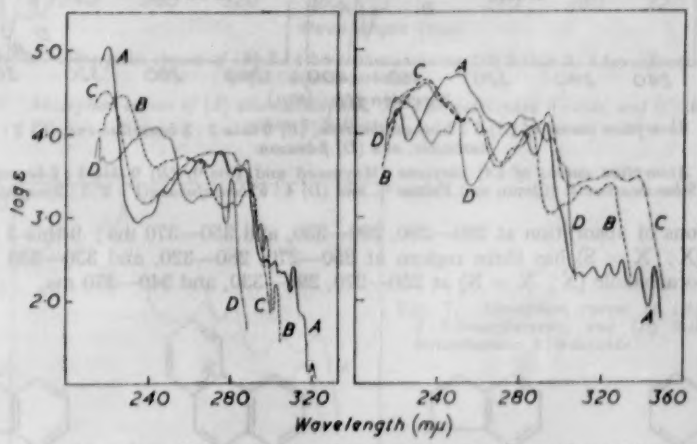


FIG. 1. *Absorption curves of (A) naphthalene* (Mayneord and Roe [4]), *(B) thionaphthen, (C) indole, and (D) benzofuran.*

FIG. 2. *Absorption curves of (A) phenanthrene, (B) dibenzothiophen, (C) carbazole, and (D) dibenzofuran.*

compounds the oxygen-compound, dibenzofuran, shows less resemblance to the aromatic hydrocarbon, and only two regions of absorption are clearly resolved (220—250 and 270—300 mμ).

The same pattern is repeated with 1 : 2-benzanthracene (V) and the related heterocyclic compounds (VI): the group I absorption occurs at shorter wavelengths with the heterocyclic compounds, and their group III absorption is much more intense than that of the hydrocarbon (Fig. 3). Thus 1 : 2-benzanthracene (V) shows three main regions of absorption, at 275—290, 320—360, and 370—390 mμ; 9-thia-2 : 3-benzofluorene (VI; X = S) shows three main regions at 260—275, 310—330, and 350—370 mμ; and 2 : 3-benzocarbazole (VI; X = N) absorbs at 260—280, 310—330, and 370—400 mμ. The oxygen derivative in this series, β-brazan (VI; X = O), has an absorption curve which does show the three main regions of absorption characteristic of its analogues, but the group III bands are shifted to much shorter wavelengths and are more intense than those of the hydrocarbon.

These conclusions apply with equal force to the two remaining series (VII, VIII; IX, X) of tetracyclic compounds (Figs. 4 and 5). Chrysene [4] has three main regions of absorption at 250—270, 280—320, and 340—360 mμ. 9-Thia-1 : 2-benzofluorene (VIII; X = S) has three main bands at 240—280, 290—310, and 325—355; 1 : 2-benzocarbazole (VIII;

[4] Mayneord and Roe, *Proc. Roy. Soc.*, 1935, *A*, **152**, 299.

X = N) has three main bands at 240—260, 270—310, and 330—360 mμ; and 4′ : 5′-benzofurano(1′ : 2′-1 : 2)naphthalene (VIII; X = O) has three main regions of absorption at 250—260, 270—310, and at 320—340 mμ. Similarly 3 : 4-benzophenanthrene (IX) has

Fig. 3.

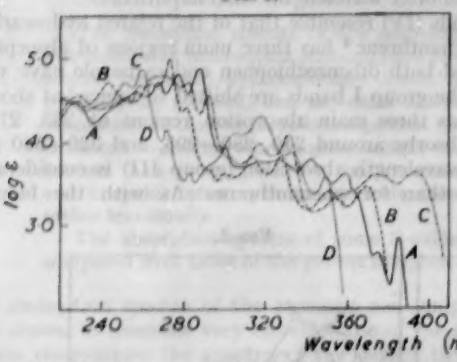


Fig. 4.

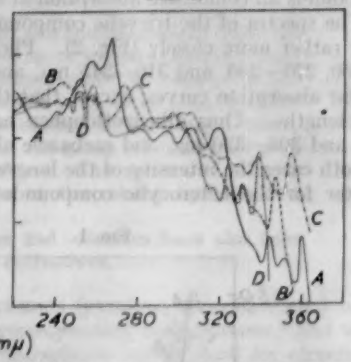
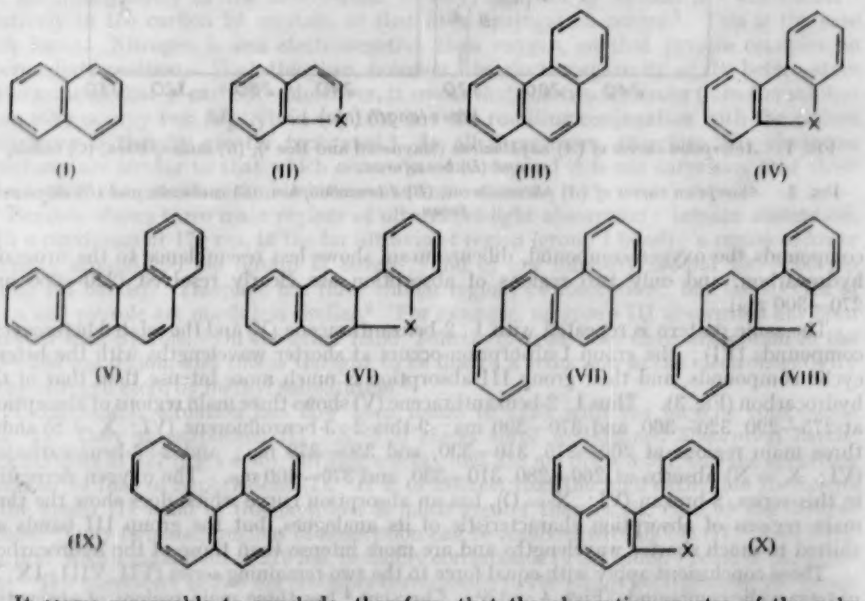


Fig. 3. *Absorption curves of* (*A*) 1 : 2-*benzanthracene*, (*B*) 9-*thia*-2 : 3-*benzofluorene*, (*C*) 2 : 3-*benzocarbazole, and* (*D*) β-*bruzan*.

Fig. 4. *Absorption curves of* (*A*) *chrysene* (Mayneord and Roe [5]), (*B*) 9-*thia*-1 : 2-*benzofluorene*, (*C*) 1 : 2-*benzocarbazole* (Clemo and Felton [5]), *and* (*D*) 4 : 5′-*benzofurano*(1′ : 2′-1 : 2)*naphthalene*.

three regions of absorption at 260—280, 290—330, and 350—370 mμ; 9-thia-3 : 4-benzofluorene (X; X = S) has three regions at 250—270, 280—320, and 330—350 mμ; and 3 : 4-benzocarbazole (X; X = N) at 250—270, 290—330, and 340—370 mμ.



It seems reasonable to conclude, therefore, that the absorption spectra of the polycyclic compounds derived from the five-membered heterocyclic systems are fundamentally similar to those of the related benzenoid hydrocarbons. Three main regions of absorption

[5] Clemo and Felton, *J.*, 1952, 1658.

FIG. 5.

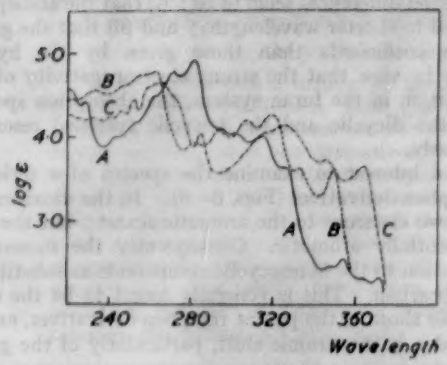


FIG. 6.

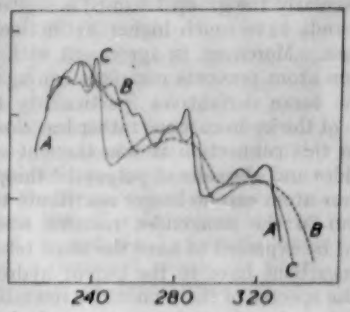


FIG. 5. *Absorption curves of (A) 3 : 4-benzophenanthrene, (B) 9-thia-3 : 4-benzofluorene, and (C) 3 : 4-benzocarbazole.*

FIG. 6. *Absorption curves of (A) dibenzothiophen, (B) dibenzothiophen 9-oxide, and (C) dibenzothiophen 9 : 9-dioxide.*

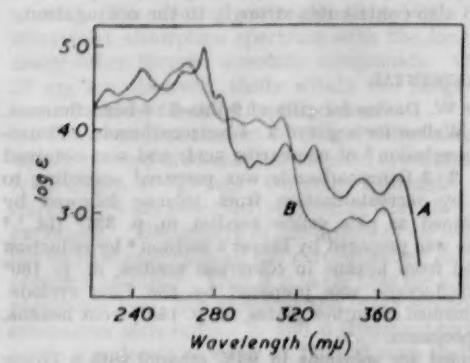


FIG. 7. *Absorption curves of (A) 9-thia-2 : 3-benzofluorene, and (B) 9-thia-2 : 3-benzofluorene 9 : 9-dioxide.*

FIG. 8.

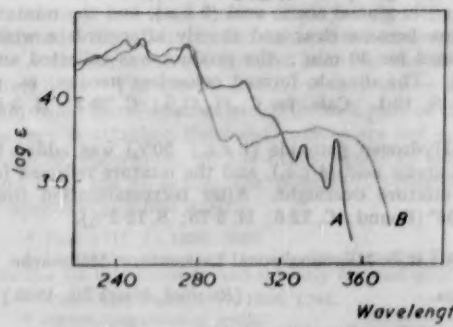
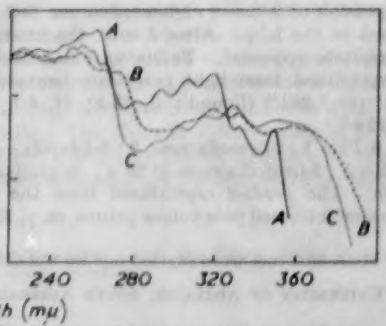


FIG. 9.



Wavelength (mμ)

FIG. 8. *Absorption curves of (A) 9-thia-1 : 2-benzofluorene and (B) 9-thia-1 : 2-benzofluorene 9 : 9-dioxide.*

FIG. 9. *Absorption curves of (A) 9-thia-3 : 4-benzofluorene, (B) 9-thia-3 : 4-benzofluorene 9-oxide, and (C) 9-thia-3 : 4-benzofluorene 9 : 9-dioxide.*

comparable to the group I, II, and III bands of the aromatic hydrocarbons and aza-compounds can generally be resolved. The chief differences seem to be: (i) that the absorption (particularly the group I bands) is shifted to shorter wavelengths; and (ii) that the group III bands have much higher extinction coefficients than those given by the hydrocarbons. Moreover, in agreement with the view that the strong electronegativity of the oxygen atom prevents complete conjugation in the furan system, the absorption spectra of the furan derivatives (particularly the dicyclic and the tricyclic systems) resemble those of the hydrocarbons rather less closely.

In this connection it was thought of interest to examine the spectra of a series of *S*-oxides and -dioxides of polycyclic thiophen derivatives (Figs. 6—9). In the dioxides the sulphur atom can no longer contribute two electrons to the aromatic sextet; but the ring system in the monoxides remains essentially aromatic. Consequently the monoxides would be expected to have the same relation to the heterocyclic compounds as substituted hydrocarbons have to the parent hydrocarbon. This is generally found to be the case, for the spectra of the monoxides resemble those of the parent thiophen derivatives, except that there is a loss of fine structure and a bathochromic shift, particularly of the group III bands.

The spectra of the dioxides, in which the hetero-ring is no longer aromatic, nevertheless show a pronounced similarity to those of the parent ring system and of the corresponding monoxides. For example, dibenzothiophen 9 : 9-dioxide shows a much greater similarity to dibenzothiophen than to 9 : 10-dihydrophenanthrene, which it might be expected to parallel. It is evident that the SO_2 group also contributes strongly to the conjugation.

Experimental

Materials.—We are indebted to Professor W. Davies for gifts of 9-thia-3 : 4-benzofluorene, and of its oxide and dioxide, and to Dr. I. S. Walker for a gift of 3 : 4-benzocarbazole. Benzofuran was prepared in 84% yield by decarboxylation [6] of coumarilic acid, and was obtained as a colourless oil, b. p. 174° (lit., 174°). 2 : 3-Benzocarbazole was prepared according to Bucherer and Sonnenburg,[7] and purified by recrystallisation from toluene followed by sublimation in a high vacuum; it was obtained as pale yellow needles, m. p. 337° (lit.,[7,8] 330—332°; 340°). 9-Thia-2 : 3-benzofluorene was prepared by Mayer's method [8] by reduction of the corresponding quinone; it crystallised from hexane in colourless needles, m. p. 160° (lit.,[8,9] 154—155°; 160°). 9-Thia-1 : 2-benzofluorene was prepared by the Elbs cyclodehydration of 3-*o*-toluoylthionaphthen [10] and formed colourless plates, m. p. 185°, from hexane. Other compounds were purified commercial specimens.

Absorption Spectra.—These were determined for solutions in 95% ethanol with a Hilger Uvispek spectrophotometer.

9-*Thia*-2 : 3-*benzofluorene* 9 : 9-*Dioxide.*—Hydrogen peroxide (1 c.c.; 30%) was added to a suspension of 9-thia-2 : 3-benzofluorene (0·2 g.) in glacial acetic acid (3 c.c.), and the mixture raised to the b. p. After 3 min. the mixture became clear and shortly afterwards a white precipitate appeared. Refluxing was continued for 30 min.; the product was collected and recrystallised from light petroleum–benzene. The dioxide formed colourless needles, m. p. 267° (lit.,[8] 261°) (Found: C, 72·4; H, 4·1; S, 12·1. Calc. for $C_{14}H_{10}O_2S$: C, 72·2; H, 3·8; S, 12·0%).

9-*Thia*-1 : 2-*benzofluorene* 9 : 9-*Dioxide.*—Hydrogen peroxide (1 c.c.; 30%) was added to 9-thia-1 : 2-benzofluorene (0·25 g.) in glacial acetic acid (4 c.c.), and the mixture refluxed for 2 hr. The *product* crystallised from the mixture overnight. After recrystallisation from benzene it formed pale yellow prisms, m. p. 236° (Found: C, 72·5; H, 3·75; S, 12·2%).

Microanalyses were carried out by the C.S.I.R.O. Microanalytical Laboratory, Melbourne.

University of Adelaide, South Australia. [*Received, March 5th*, 1956.]

[6] Cf. Shepard, Winslow, and Johnson, *J. Amer. Chem. Soc.*, 1930, **52**, 2083.
[7] Bucherer and Sonnenburg, *J. prakt. Chem.*, 1910, **81**, 29.
[8] Mayer, *Annalen*, 1931, **488**, 259.
[9] Werner, *Rec. Trav. chim.*, 1949, **68**, 520.
[10] Badger and Christie, preceding paper.

667. *Pteridine Studies. Part IX.* The Structure of the Monohydroxypteridines and their N-Methyl Derivatives.*

By D. J. Brown and S. F. Mason.

To decide between a number of possible tautomeric structures for the four monohydroxypteridines, their infrared and ultraviolet spectra and ionisation constants have been compared with those of the *N*-methyl derivatives, including some new derivatives not obtained by direct methylation. It is concluded that all the monohydroxypteridines have the –CO·NH– structure, that is, they are cyclic amides and not vinylogous amides or hydroxy-derivatives. It is suggested that the strongly bound molecule of water in 2- and 6-hydroxypteridine and their *N*-methyl derivatives is water of constitution, and is added across the 3 : 4- and the 7 : 8-double bond respectively. The ready introduction of a hydroxyl group on gentle oxidation, but only in those cases where water of constitution has been assumed, strengthens this hypothesis.

The monohydroxypteridines may be divided into two classes. The 4- and the 7-isomers possess properties expected of tetra-azanaphthalenes with a hydroxyl group α or γ to a ring-nitrogen atom. They are acids with pK_a values of 7·89 and 6·41 respectively (Table 1), that is, they are acids some 10—1000 times stronger than the analogous hydroxytriazanaphthalenes which in turn are stronger than the corresponding diazanaphthalene derivatives.[1] The neutral molecules of 4- and 7-hydroxypteridine possess a three-banded ultraviolet absorption spectrum with the long-wavelength band just above 300 mμ, like many other bicyclic aromatic compounds. On anion formation, bathochromic shifts of 23 mμ are observed, shifts within the range of 6—34 mμ found for other (potentially tautomeric) hydroxyazanaphthalenes.[2]

The neutral molecules of 2- and 6-hydroxypteridine, on the other hand, give only a double-banded ultraviolet absorption spectrum, the long-wavelength band of the 6-isomer lying as low as 289 mμ. On anion formation, large bathochromic shifts of 68 and 67 mμ respectively are observed, suggesting that the anions are more conjugated than the neutral molecules. The spectra of the anions of all four monohydroxypteridines resemble those of the neutral molecules of the corresponding amines,[3,4] as is general for phenoxide ions and aromatic amines.[5] Thus it is likely that the anions of 2- and 6-hydroxypteridine are normal phenoxide ions, like those of the other isomers, and that the neutral molecules possess anomalous structures. 2- and 6-Hydroxypteridine differ from their isomers in that they retain a molecule of water at 110°, though their sodium salts are anhydrous. 2-Hydroxypteridine loses this water at 180°, and the 6-isomer decomposes at this temperature without prior dehydration.[6,7] Again, 2-hydroxypteridine is a much weaker acid (pK_a 11·13) than its isomers, and the 6-isomer displays hysteresis on titration, giving a pK_a value of 9·7 when titrated with alkali and the value of 6·7 when the anion is titrated with acid.

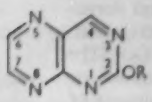
A similar contrast obtains between the *N*-methyl derivatives of the monohydroxypteridines. The known *N*-methyl derivatives of 4- and 7-hydroxypteridine are anhydrous, and when the *N*-methyl group forms a part of the ring in the pteridine nucleus to which the oxygen is attached these derivatives are not acidic. The *N*-methyl derivatives of 2- and 6-hydroxypteridine, on the other hand, all possess a strongly bound molecule of water, and they are all acidic, the *N*-methyl-2-pteridones † having pK_a values close to that of 2-hydroxypteridine itself.

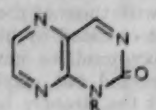
* Part VIII, *J.*, 1956, 2066.

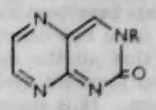
† We prefer this name to dihydro-*N*-methyl-2-oxopteridines which the Editor states is correct practice for this *Journal*; and similarly for analogous mono "amides."

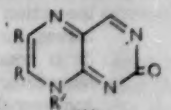
[1] Albert and Phillips, *J.*, 1956, 1294.
[2] Mason, unpublished work.
[3] Albert, Brown, and Cheeseman, *J.*, 1951, 474.
[4] *Idem*, *J.*, 1952, 1620.
[5] Jones, *J. Amer. Chem. Soc.*, 1945, **67**, 2127.
[6] Albert in the Symposium report, "The Chemistry and Biology of Pteridines," Churchill, London, 1954, p. 204.
[7] Albert, *J.*, 1955, 2690.

2-Hydroxypteridine.—It has been shown [6] that the ultraviolet spectra of 2-hydroxy- and 2-methoxy-pteridine (I; R = Me) in aqueous solution are dissimilar. Hence, 2-hydroxypteridine should exist mainly as a cyclic amide in that solvent. 2-Hydroxypteridine in the solid state, and its 6 : 7-diethyl derivative in chloroform solution, show a strong band in the C:O stretching vibration region of the infrared, but its sodium salts and *O*-methyl derivative do not, and so the former compounds exist as cyclic amide under the


(I)


(II)


(III)


(IV)

conditions stated. The alternative amide structures are (II—IV; R = R′ = H), and spectroscopic comparison of 2-hydroxypteridine with the corresponding *N*-methyl derivatives (II—IV, R = R′ = Me) allows a choice to be made between them.

Of the three possible *N*-methyl-2-pteridones, the 3-isomer (III; R = Me) is known and

TABLE 1. *The ultraviolet absorption spectra of the monohydroxypteridines and their N-methyl derivatives.* (*Values in italics refer to shoulders or inflexions.*)

Compound	pK_a in H_2O at 20° and concn.	pH at which spectrum was measured	$\lambda_{max.}$ (mμ)	log ε
2-Hydroxypteridine [a] (+1H_2O)	—	7·1	230; *285*; 307	3·88; *3·59*; 3·83
anion [a]	11·13	13·0	260; 375	3·85; 3·78
cation [a]	<2	—	—	—
1-Methyl-2-pteridone (+1H_2O)	—	7·0	240; *285*; 311	3·91; *3·53*; 3·85
anion	11·43 [d]	13·0	236; 312; 375	3·89; 3·81; 2·37
cation	<1	—	—	—
3-Methyl-2-pteridone (+1H_2O)	—	7·0	230; *285*; 309	3·97; *3·59*; 3·89
anion	11·01 [d]	13·0	236; 271; 313; *350*	3·84; 3·66; 3·80; *3·53*
cation	<1	—	—	—
3 : 6 : 7-Trimethyl-2-pteridone (+1H_2O)	—	7·0	235; *290*; 317	3·95; *3·60*; 4·02
anion	11·36(±0·01), M/20	13	236; 277; 319; *355*	3·90; 3·53; 4·01; 3·23
cation	<2	—	—	—
6 : 7 : 8-Trimethyl-2-pteridone	—	7·0	239; *280*; 327	4·34; *3·70*; 4·25
anion	10·26(±0·04), M/400	12·3	240; 344	4·23; 4·19
cation	<2	—	—	—
4-Hydroxypteridine [a]	—	5·6	230; 265; 310	3·98; 3·54; 3·82
anion [a]	7·89	10·0	242; 333	4·23; 3·79
cation	−0·17(±0·07), [e] M/10	−2·5 [b]	267; 303	3·43; 3·96
1-Methyl-4-pteridone	—	7·0	232; *260*; *300*; 324	4·14; *3·34*; *3·41*; 3·96
cation	1·25(±0·05), M/20	−0·8 [c]	225; 263; 305	4·11; 3·49; 4·03
3-Methyl-4-pteridone	—	5·3	233; 276; 312	4·12; 3·57; 3·81
cation	−0·47(±0·03), [e] M/10	−2·5 [b]	221; *265*; 304	4·04; *3·46*; 4·00
6 : 7 : 8-Trimethyl-4-pteridone	—	7·0	236; 256; 301 + 311; 392	4·09; 4·14; 4·10 + 4·13; 3·55
anion	9·46(±0·05)	12·0	237; 269; 297; 334; *375*	4·24; 4·04; 3·91; 3·68; *3·45*
cation	4·70(±0·07)	2·5	246; 279; 356	3·97; 3·58; 4·02
6-Hydroxypteridine [f] (+1H_2O)	—	—	—	—
stable neutral molecule	—	5·2	*266*; 289	*3·85*; 4·00
transient neutral molecule	—	5·2	230; 305; 332	3·80; 3·65; 3·66
cation [b]	3·67	1·7	287	4·09
stable anion	6·7	13·0	224; 256; 356	4·29; 3·97; 3·84
transient anion	9·7	13·0	*265*; 289	*3·84*; 3·99
5-Methyl-6-pteridone (+1H_2O)	—	7·0	*265*; 290	*3·85*; 4·06
anion	10·6 [d]	13·0	*270*; 296	*3·78*; 3·99
cation	3·73	1·0	288	4·14

[a] Albert, Brown, and Cheeseman, *J.*, 1952, 4219.

TABLE 1. (*Continued.*)

Compound	pK_a in H_2O at 20° and concn.	pH at which spectrum was measured	$\lambda_{max.}$ (mμ)	log ε
7 : 8-Dihydro-6-hydroxypteridine [b]	—	7·4	*275*; 293	*3·80*; 3·93
anion	10·54	13·0	*275*; 305	*3·75*; 4·07
cation [b]	4·78	2·4	292	4·01
7-Hydroxypteridine [b]	—	4·0	227; 248 + 256; 303	3·79; 3·44 + 3·45; 4·00
anion [b]	6·41	9·0	226; 260; 326	4·27; 3·76; 4·04
cation [b]	1·2	—	—	—
8-Methyl-7-pteridone [b]	—	4·0	<220; 250 + 257; 300	>4·13; 3·55 + 3·54; 3·97
cation	1·1	−2·0 [j]	295	3·97
5 : 6-Dihydro-7-hydroxypteridine [b]	—	6·0	271; 319	3·58; 3·70
anion	9·94	12·0	224; *265*; 325	4·34; *3·56*; 3·93
cation [b]	3·36	1·0	233; 284; 352	4·47; 3·74; 3·71
5 : 6-Dihydro-6 : 7-dihydroxy-5-methylpteridine	—	7·0	259; 315	3·74; 3·88
anion	9·33(±0·03), M/100	11·4	226; *268*; 322	4·26; *3·71*; 4·05
cation	2·91(±0·02), M/100	0·7	225; 275; 334	4·41; 3·78; 3·8
5 : 6-Dihydro-5 : 8-dimethyl-6-hydroxy-7-pteridone	—	7·0	219; 260; 315	4·44; 3·75; 3·93
6 : 7-Dihydroxypteridine [b]	—	4·0	249 + 255; 301	3·71 + 3·70; 4·18
anion [b]	6·87	8·4	227; 268; 319	4·03; 3·71; 4·29
dianion [b]	10·0	12·0	240; 277; *319* + 324 + 338	4·13; 3·68; *4·09* + 4·30 + 4·25
7-Hydroxy-5-methyl-6-pteridone	—	—	—	—
anion	7·02(±0·03), M/100	13·0	237; 268; 309 + 321 + 336	4·01; 3·65; 4·24 + 4·36 + 4·20
5 : 6 : 7 : 8-Tetrahydro-5 : 8-dimethyl-6 : 7-dioxopteridine	—	7·0	223; 254 + 261; 303	4·11; 3·66 + 3·68; 4·20
2-Hydroxyquinoline	—	4·7	224; 245; 270; 323	4·43; 3·93; 3·82; 3·80
anion	11·74 [f]	13·7	232; 332	4·65; 3·74
cation	−0·31 [f]	−2·5 [k]	238; 299	4·34; 3·88
2-Hydroxyquinazoline	—	5·0	220; 274; 345	4·42; 3·57; 3·25
anion	10·69 [f]	13·0	230; 322; 351	4·51; 3·35; 3·41
cation	1·30 [f]	−0·8 [g]	220; 292; 385	4·53; 3·98; 3·42
1-Methyl-5-quinolone	—	8·5	237; 273; 318 + 332; 462	4·06; 4·52; 3·09 + 3·06; 3·58
cation	6·12(±0·04), M/100	3·0	222; 254; 305 + 318; 376	3·90; 4·62; 3·20 + 3·26; 3·50
1-Methyl-7-quinolone	—	8·0	261; 311; 406	4·51; 3·19; 4·00
cation	5·56(±0·02), M/100	2·0	245; 308; 353	4·54; 3·50; 3·92
2-Methyl-6-*iso*quinolone	—	10·0	230; 267; 358	4·54; 4·36; 4·09
cation	6·10(±0·05), [g] M/10⁴	2·0	227; 246; 319	4·55; 4·50; 3·96
2-Aminopyrazine	—	7·0	230; *285*; 316	4·02; *3·33*; 3·70
cation	3·14 [g]	1·0	229; 325	4·03; 3·77
2-Acetamidopyrazine	—	7·0	231; 280; 296	4·16; 3·81; 3·81
3-Aminopyrazine-2-carboxyamide	—	6·1	246; 305; 350	4·06; *3·26*; 3·80
3-Aminopyrazine-2-carboxylic acid	—	6·1	244; *295*; 340	4·01; *3·29*; 3·76
4 : 5-Diamino-2-hydroxypyrimidine [e]	—	6·98	292	3·58
anion [e]	11·45	13·0	226; 303	3·91; 3·67
cation [e]	4·37	2·3	305	3·76
4 : 5-Diamino-6-hydroxypyrimidine [e]	—	6·7	278; 372	3·95; 2·44
anion [e]	9·86	12·0	272; 370	3·87; 2·62
cation [e]	3·57; 1·34	2·45	258	3·74

[a] Albert *et al.*, *J.*, 1951, 474. [b] Albert *et al.*, *J.*, 1952, 1620. [c] Mason, *J.*, 1954, 2071. [d] Albert *et al.*, *J.*, 1956, 2066. [e] Determined spectroscopically. [f] Albert and Phillips, *J.*, 1956, 1294. [g] Albert, Goldacre, and Phillips, *J.*, 1948, 2240. [h] 10N-Sulphuric acid; these compounds slowly decompose at this pH. [i] 4N-Sulphuric acid. [j] 7·5N-Sulphuric acid.

an isomer has been obtained by the methylation of 2-hydroxypteridine.[9] Attempts to synthesise the 8-isomer (IV; R = H, R′ = Me) from 5-amino-2-hydroxy-4-methylaminopyrimidine and glyoxal did not give the required substance, but condensation of the same pyrimidine with diacetyl afforded 6 : 7 : 8-trimethyl-2-pteridone (IV; R = R′ = Me). The ultraviolet spectrum of this compound, and the infrared spectrum in the N–H and C:O stretching regions, are markedly different from those of the above two isomers (Fig. 1, Tables 1 and 2).* Thus, by elimination, the methylation product of 2-hydroxypteridine must be 1-methyl-2-pteridone.

The molecule of water held by these three *N*-methyl-2-pteridones is strongly bound; indeed, 1- and 3-methyl-2-pteridone cannot be dehydrated without fundamental change. When heated above their softening points (160—230°), the latter compounds are converted into new, water-insoluble substances, which, although very hygroscopic, do not revert to the original materials save on dissolution in alkali and reprecipitation with acid. 3 : 6 : 7-Trimethyl-2-pteridone (as hydrate or ethanolate) gives a similar compound above 190°, but the latter does not revert cleanly to the original substance when treated as above with

FIG. 1. FIG. 2.

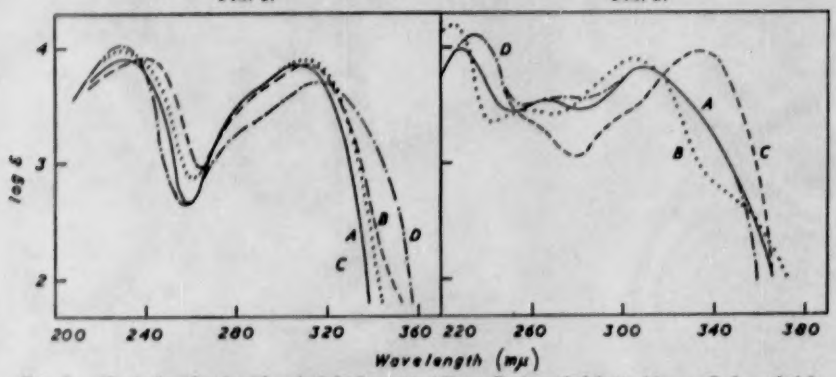


FIG. 1. *Neutral molecules of : A, 2-hydroxypteridine; B, 1-methyl-2-pteridone; C, 3-methyl-2-pteridone; and D, 2-aminopyrazine.*

FIG. 2. *Neutral molecules of : A, 4-hydroxypteridine; B, 4-methoxypteridine; C, 1-methyl-4-pteridone; and D, 3-methyl-4-pteridone.*

alkali. From their general properties, these products obtained by vigorous heating seem to be dimeric or polymeric, and they may be analogous to the dimers obtained from 6-hydroxypteridine.[7] 6 : 7 : 8-Trimethyl-2-pteridone becomes anhydrous at 120° *in vacuo*, but is readily rehydrated in air at room temperature.

The *N*-methyl-2-pteridones possess properties which suggest that the strongly bound molecule of water may be water of constitution. Their formal structures (II—IV; R = R′ = Me) show no acidic groupings or N–H linkages, yet they may be dissolved in alkali and reprecipitated unchanged with acid, and in chloroform or carbon tetrachloride solution they show a band in the infrared due to a N–H stretching vibration (Table 2). The band persists, and lies in the same position, when the molecule of water is exchanged for alcohol, an exchange effected by a few recrystallisations from ethanol in the case of the more soluble compounds, namely, 1-methyl- and 3 : 6 : 7-trimethyl-2-pteridone. The hydrates, but not the alcoholates, of these compounds also show a weak band in the O–H stretching vibration region. When 6 : 7 : 8-trimethyl-2-pteridone has been heated at 120° *in vacuo*, its infrared spectrum shows a N–H stretching vibration band much reduced in intensity, though the

* In principle, the *C*-methyl groups in positions 6 and 7 of 6 : 7 : 8-trimethyl-2-pteridone can have little effect in the spectral regions examined. In the analogous case of 3 : 6 : 7-trimethyl-2-pteridone (from diacetyl and 4 : 5-diamino-1 : 2-dihydro-1-methyl-2-oxopyrimidine) the N–H and C : O stretching frequencies, and the ultraviolet spectrum, are closely similar to those of, for example, 3-methyl-2-pteridone (Tables 1 and 2).

[9] Albert, Brown, and Wood, *J.*, 1956, 2066.

band cannot be eliminated, owing perhaps to the difficulty of maintaining the compound anhydrous. Both the "hydrate" and the "alcoholate" of 6 : 7-diethyl-2-hydroxypteridine (2-hydroxypteridine hydrate is insoluble in non-polar solvents) show two bands

TABLE 2. *The infrared spectra of the monohydroxypteridines, their sodium salts, and their N-methyl derivatives in the* O–H, N–H, *and double-bond stretching vibration regions.*

(vs = very strong, s = strong, m = moderate, w = weak.)

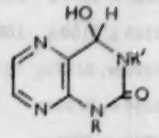
	O–H and N–H stretching frequencies ($cm.^{-1}$)			Double-bond stretching frequencies ($cm.^{-1}$)	
Compound	In CCl_4	In $CHCl_3$	Solid	In $CHCl_3$	Solid
2-Hydroxypteridine ($+1H_2O$)	[b]	[b]	3335 w, 3256 s	[b]	1681 vs, 1598 s
deuterated	[b]	[b]	2325 s		1672 vs, 1595 s
sodium salt	[b]	[b]	—		1614 s
2-Methoxypteridine [a]	[c]	[c]	—	[c]	1598 s
6 : 7-Diethyl-2-hydroxypteridine ($+1H_2O$ or 1EtOH)	3439 s, 3389 s	3424 s, 3382 s	—	1705 s	—
1-Methyl-2-pteridone ($+1H_2O$ or 1EtOH)	3434 s	3426 s	3350 w, 3233 s, 3124 s	1688 s	1685 s, 1555 s
3-Methyl-2-pteridone ($+1H_2O$)	[b]	3421 s	3260 s, 3180 s	1690 s	1670 s, 1600 s
3 : 6 : 7-Trimethyl-2-pteridone ($+1H_2O$ or 1EtOH)	3433 s	3423 s	3245 s, 3150 s	1690 s	1670 s, 1601 s
6 : 7 : 8-Trimethyl-2-pteridone	3422 m	3414 m	3290 w, 3183 m	1654 s	1653 s, 1595 s
4-Hydroxypteridine		[b]	3380 w, 3130 m	[b]	1710 s, 1697 s, 1586 s
deuterated	[b]	[b]	2320 m, 2205 m	[b]	1690 s, 1605 m, 1583 s
sodium salt	[b]	[b]	—	[b]	1611 w, 1584 s
4-Methoxypteridine [a]	[c]	[c]	—	[c]	1578 s
6 : 7-Diethyl-4-hydroxypteridine	3401 s	3387 s	—	1685 s	—
6 : 7-Diethyl-2 : 4-dihydroxypteridine	3421 s, 3408 s	3402 s, 3386 s	—	1703 s, 1684 s	—
1-Methyl-4-pteridone	[c]	[c]	—	1740 s, 1678	1664 s, 1607 s
3-Methyl-4-pteridone	[c]	[c]	—	1702 s	1671 s, 1595 s
6 : 7 : 8-Trimethyl-4-pteridone	[b]	3388 w	3272 w, 3140 w	1705 s, 1670 s	1681 s, 1606 s
6-Hydroxypteridine ($+1H_2O$)	[b]	[b]	3352 w, 3210 s 3172 s, 3117 s	[b]	1681 s, 1608 s
deuterated	[b]	[b]	2330 s, 2170 s	[b]	1670 s, 1594 s
sodium salt	[b]	[b]	—	[b]	1592 s
6-Methoxypteridine [a]	[c]	[c]	—	[c]	1591 s
5-Methyl-6-pteridone ($+1H_2O$)	[b]	[b]	3350 w, 3205 s 3160 s	[b]	1689 s, 1596 s
7-Hydroxypteridine	[b]	[b]	3305 w, 3242 m 3138 s	[b]	1693 s, 1580 s
deuterated	[b]	[b]	2295 m, 2270 m	[b]	1690 s, 1580 s
sodium salt	[b]	[b]	—	[b]	1605 m, 1576 s
7-Methoxypteridine [a]	[c]	[c]	—	[c]	1591 m, 1570 s
8-Methyl-7-pteridone	[c]	[c]	—	1688 s	1676 s, 1573 s
6 : 8-Dimethyl-7-pteridone			—	1685 s	1675 s, 1595 s
5 : 6-Dihydro-6-hydroxy-5-methyl-7-pteridone		[b]	3345 w, 3223 m 3165 s	[b]	1676 s, 1578 s
5 : 6-Dihydro-5 : 8-dimethyl-6-hydroxy-7-pteridone	3566 m		3275 m	1689 s	1678 s, 1582 s

[a] Mason, *J.*, 1955, 2336. [b] Insufficiently soluble. [c] Soluble, but no band was observed in this region. [d] Region obscured by solvent absorption.

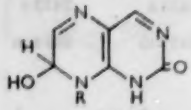
in the N–H stretching vibration region and when either form is heated at 120° *in vacuo* the band at higher frequency (3430 $cm.^{-1}$), corresponding to the band observed in the spectra of the *N*-methyl-2-pteridones, is reduced in intensity. In the solid state the *N*-methyl-2-pteridones show broad bands in the 3400—3100 $cm.^{-1}$ region due to intermolecularly hydrogen bonded O–H and N–H groups, whilst the unhydrated *N*-methyl-4- and -7-pteridones show no absorption above 3100 $cm.^{-1}$.

It is unlikely that these " hydrates " possess the open-ring structures typified by those derived by hydrolytic cleavage of the 1 : 2- or 7 : 8-double bond of (II), as they give negative tests for an aldehyde group with benzidine and are too weak both as acids (Table 1) and bases ($pK_a < 1$). More plausible are the structures (V; R or R′ = H) and (VI) in which the molecule of water has added across one of the nuclear double bonds. These structures indicate that the ultraviolet spectra of 2-hydroxypteridine and its *N*-methyl derivatives should be those of a substituted pyrimidine (VI) or a substituted pyrazine (V). 2-Hydroxypteridine hydrate and its 1- and 3-methyl derivative do indeed possess ultraviolet spectra (Fig. 1, Table 1) which are similar to those of 2-amino- and 2-acetamido-pyrazine and different from those of 2-hydroxy-quinoline and -quinazoline, the last two compounds having chromophore structures similar to that of the anhydrous 2-hydroxypteridine. 6 : 7 : 8-Trimethyl-2-pteridone, on the other hand, has an ultraviolet spectrum more akin to that of *N*-methyl-7-quinolone than to that of 4 : 5-diamino-2-hydroxypyrimidine (Table 1), though the latter compound does not provide so exact a model chromophore for (VI) as 2-acetamidopyrazine does for (V).

The balance of evidence accordingly suggests that 2-hydroxypteridine hydrate possesses the structure (V; R = R′ = H). The close similarity between the ultraviolet spectra of



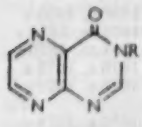
(V)



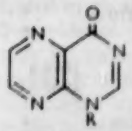
(VI)

2-hydroxypteridine and those of its 1- and 3-methyl derivative indicates that they all have the same chromophoric structure (Fig. 1, Table 1). When the hydration of these compounds is taken into account, this structure is likely to be (V), for if the molecule of water had added elsewhere in the pteridine nucleus than across the 3 : 4-positions (or 1 : 4 in the case of the 3-methyl derivative) then 1- and 3-methyl-2-pteridone would form different chromophoric structures and probably would possess different ultraviolet spectra. Oxidation affords additional evidence that 2-hydroxypteridine hydrate has the structure (V; R = R′ = H), which is the dihydro-derivative of 2 : 4-dihydroxypteridine. Potassium permanganate converts it in good yield at 20° into 2 : 4-dihydroxypteridine, whilst 4-hydroxypteridine, which possesses no water of constitution, is not attacked by this reagent even at 100°.

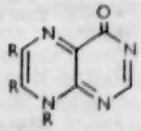
Structure (V) accounts for the weak, and nearly equal, acid strengths of 2-hydroxypteridine and its 1- and 3-methyl derivative (Table 1), for the acidity is due to the ureido-



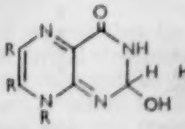
(VII)



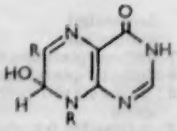
(VIII)



(IX)



(X)



(XI)

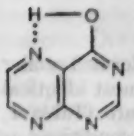
portion of (V), in which the $N_{(1)}$–H group might be expected to be nearly equivalent to the $N_{(3)}$–H group but slightly more acidic owing to the electron-withdrawing effect of the pyrazine ring. In the anions of 1- and 3-methyl-2-pteridone the 3- and the 1-nitrogen atom respectively carry a substantial negative charge, and the compounds no longer have the same chromophoric structure. Thus the ultraviolet spectra of the anions of 1- and 3-methyl-2-pteridone differ one from the other, and also from that of the anion of 2-hydroxypteridine (Table 1) which is probably a true phenoxide ion (see above), having lost the water of constitution.

4-Hydroxypteridine.—Two of the three possible *N*-methyl-4-pteridones (VII—IX; R = Me) have been prepared by the direct methylation of 4-hydroxypteridine, their

structures being confirmed by synthesis.[8,9] Attempted condensation of 5-amino-4-hydroxy-6-methylaminopyrimidine with glyoxal to provide the third isomer was not successful, but with diacetyl this pyrimidine yielded the homologue, 6 : 7 : 8-trimethyl-4-pteridone. Like the *N*-methyl-4-pteridones, this is not hydrated, though it is somewhat hygroscopic, and, unlike (VII) and (VIII), it is acidic and absorbs to a slight extent in the N–H stretching vibration region of the infrared unless it is thoroughly dried. However, the ultraviolet spectrum of 6 : 7 : 8-trimethyl-4-pteridone in neutral aqueous solution resembles that of the fully conjugated model chromophore, *N*-methyl-5-quinolone, in its qualitative features, but not those of 3-aminopyrazine-2-carboxyamide or 4 : 5-diamino-6-hydroxypyrimidine which are approximate model chromophores of the hydrated structures (X) and (XI) (Table 1).

Accordingly, 6 : 7 : 8-trimethyl-4-pteridone probably exists largely in the transannular pteridone form (IX), the acidity of the molecule arising from the union with a hydroxyl ion to give the anion of (X) or (XI). The high acid strength of the compound (pK_a 9·46), relative to that of the other *N*-methylpteridones, suggests that the resultant anion is probably that corresponding to structure (XI), for the latter is a derivative of 4 : 5-diamino-6-hydroxypyrimidine (pK_a 9·68), whilst a compound (X) is a derivative of 3-aminopyrazine-2-carboxyamide which has no acidic pK_a below 13.

4-Hydroxypteridine itself can exist to a considerable degree in the pteridone form, as it absorbs strongly in the C:O stretching vibration region of the infrared in the solid state, and so too does its 6 : 7-diethyl derivative [8] in chloroform solution. The latter compound in carbon tetrachloride solution gives rise to a single band (Table 2) in the N–H stretching vibration region, unlike the 2-hydroxy-isomer which gives two such bands, and this band lies in a range, 3370—3420 cm.$^{-1}$, which has been found to be characteristic of conjugated cyclic amides.* [2] In aqueous solution the ultraviolet spectrum of 4-hydroxypteridine resembles that of the conjugated cyclic amide (VII; R = Me), but not those of (VIII or IX; R = Me) (Fig. 2, Table 1). Some resemblances have been noted between the ultraviolet spectra of 4-hydroxypteridine and its *O*-methyl derivative,[8] and whilst these similarities are not so marked as those obtaining between the spectra of 4-hydroxypteridine and its $N_{(3)}$-methyl derivative, it is possible that an appreciable amount of the enol form (XII) exists in equilibrium with the predominant tautomer (VII; R = H). The enol form is presumably stabilised by intramolecular hydrogen bonding (XII), which is not possible with the other monohydroxypteridines. Attempts to estimate the ratio of the amounts of the isomers from the ultraviolet absorption curves of 4-hydroxypteridine and its *O*-methyl and $N_{(3)}$-methyl derivatives give results which are far from consistent at different wavelength values, and it can be concluded only that (VII; R = H) is the predominant tautomer.



(XII)

6-*Hydroxypteridine.*—The ultraviolet spectra of 6-hydroxy- and 6-methoxy-pteridine in neutral aqueous solution have been shown to be dissimilar,[4] and the former in the solid state absorbs strongly in the C:O stretching vibration region (Table 2), whilst the latter does not.[10] Thus 6-hydroxypteridine probably exists mainly in the amide form in aqueous solution and in the solid.

For valency reasons, anhydrous 6-hydroxypteridine can form only one amide structure, and thus only one *N*-methyl derivative. However, if the molecule of water bound to each molecule of 6-hydroxypteridine is constitutional, this restriction does not hold. Attempted preparation of 5-methyl-6-pteridone from 4-amino-5-methylaminopyrimidine and the hemiacetal of ethyl glyoxylate gave two products, each analysing as a hydrated "methylpteridone." One was formed by carrying out the condensation in neutral aqueous solution, the other in dilute mineral acid, and the former could be converted into

* From a study of some fifty *N*-heteroaromatic hydroxy-compounds, it has been found that those with the hydroxyl group α to a ring nitrogen atom show an N–H stretching vibration band at 3370—3420 cm.$^{-1}$, and those with a hydroxyl group γ to a ring nitrogen at 3420—3460 cm.$^{-1}$. The remainder, apart from those with an intramolecular hydrogen bond, show a band due to an O–H stretching vibration in the range 3590—3620 cm.$^{-1}$.

[10] Mason, *J.*, 1955, 2336.

the latter by treatment with dilute acid. Such behaviour is paralleled in the reaction between 4 : 5-diaminopyrimidine and ethyl glyoxylate, which gives mainly 7-hydroxypteridine under neutral conditions and the 6-isomer under acid conditions,[4] the former being converted into the latter by acid.[7]

Both of these hydrated "methylpteridones" are acids, though they are too weak (Table 1) to be carboxylic acids, and they both show negative tests for the aldehyde group with benzidine, so that they cannot possess ring-opened structures of the type derived by hydrolytic cleavage of 5-methyl-6-pteridone at the double bonds 5 : 6 or 7 : 8. The mode of formation of these "methylpteridones" suggests that they are *N*-methyl-6- and -7-hydroxypteridines. Valency considerations do not permit of a simple 5-methyl-7-pteridone, but the addition of a molecule of water of constitution to the pyrazine ring of the pteridine nucleus allows the formulation of the 7-hydroxypteridine derivative as (XIII). The hydrated "methylpteridone" formed under neutral conditions has ultraviolet spectra similar to those of 5 : 6-dihydro-7-pteridone, of which (XIII) is the

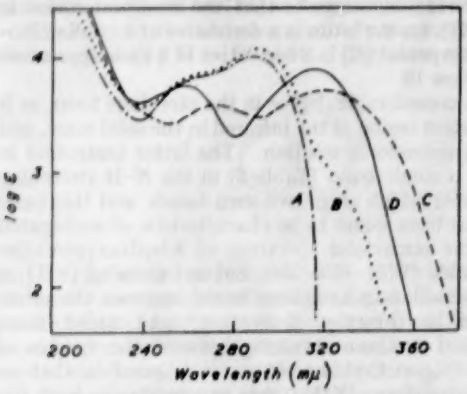
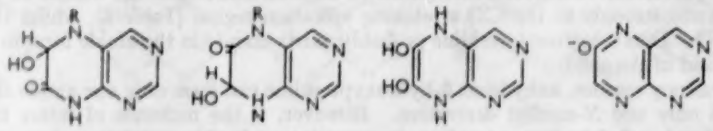


FIG. 3. *Neutral molecules of: A, 6-hydroxypteridine hydrate; B, 5-methyl-6-pteridone hydrate; C, 5 : 6-dihydro-7-hydroxypteridine; and D, 5 : 6-dihydro-6 : 7-dihydroxy-5-methylpteridine.*

6-hydroxy-5-methyl derivative, whilst the hydrated "methylpteridone" formed under acid conditions has, in its neutral and cationic forms, ultraviolet spectra almost identical with those of the corresponding ionic species of 6-hydroxypteridine hydrate (Table 1, Fig. 3). Thus the hydrated "methylpteridone" formed under neutral conditions is taken to be 5 : 6-dihydro-6-hydroxy-5-methyl-7-pteridone (XIII; R = Me), and that formed under acid conditions to be 5-methyl-6-pteridone hydrate.

Both of these compounds were oxidised by potassium permanganate at 20° to 5 : 6 : 7 : 8-tetrahydro-5-methyl-6 : 7-dioxopteridine, which was also synthesised directly from 4-amino-5-methylaminopyrimidine and diethyl oxalate. Accordingly the water of



(XIII) (XIV) (XV) (XVI)

constitution in 5-methyl-6-pteridone hydrate must be added across the 7 : 8-double bond of the pteridine nucleus, as in (XIV; R = Me). The 7 : 8-double bond in 6-hydroxypteridine is in general susceptible to additive attack. With sodium amalgam, 7 : 8-dihydro-6-hydroxypteridine is formed,[4] and hydroxylamine gives 7-amino-6-hydroxypteridine.[7] In view of the close similarity between the spectra of the cations and neutral molecules of 7 : 8-dihydro-6-hydroxypteridine, 6-hydroxypteridine hydrate, and 5-methyl-6-pteridone hydrate (Fig. 3, Table 1), it is likely that water is added across the 7 : 8-double bond in both of the latter cases, to give (XIV; R = H or Me). Structure (XIV; R = H) is the 7 : 8-dihydro-derivative of 6 : 7-dihydroxypteridine, and it is found that 6-hydroxypteridine is

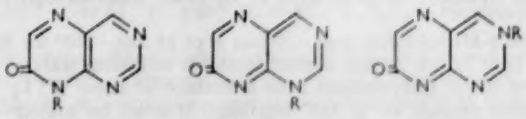
oxidised by potassium permanganate at 20° to 6 : 7-dihydroxypteridine, whilst 7-hydroxypteridine, which is not hydrated, is not attacked under these conditions.

The possible ene-diol structure (XV) for 6-hydroxypteridine hydrate is in accord with many of the above observations, but it does not explain the sensitivity of the 7 : 8-bond of 6-hydroxypteridine to additive attack. Moreover, 6-hydroxypteridine does not give a blue colour with ferric chloride and ammonia and it does not reduce the E_0 indicator, alkaline dichlorophenolindophenol, tests which are specific for ene-diols.[11]

The hydrated structure (XIV; R = H) for 6-hydroxypteridine explains the hysteresis observed on the titration of the compound with alkali followed by back-titration with acid.[4] Freshly neutralised solutions of the anion of 6-hydroxypteridine give an ultraviolet spectrum (Table 1) different from that of the stable neutral molecule, though the spectrum reverts in a few minutes to that of the latter. Similarly, the spectrum of the stable anion of 6-hydroxypteridine is not observed until several minutes after a solution of the stable neutral molecule is made alkaline. The spectrum of the transient unstable anion of 6-hydroxypteridine appears to be similar to that of the stable neutral molecule, just as the spectra of the anion and neutral species of 5-methyl-6-pteridone hydrate resemble one another (Table 1), suggesting, in both cases, that the conjugated structures of the two ionic species are similar. On the other hand, the transient neutral molecule of 6-hydroxypteridine absorbs at a longer wavelength than the stable neutral molecule, indicating that the former possesses a more conjugated structure than the latter.

Evidence has been presented (see above) that the stable anion of 6-hydroxypteridine has the structure (XVI), with no water of constitution. The pK_a value (6·7) observed when this anion is titrated quickly with acid supports such a view, since the pK_a of the unhydrated 7-isomer is 6·41. The transient neutral molecule, retaining the full naphthenoid conjugation, is formed presumably by addition of a proton to the 5-nitrogen atom or the oxygen atom, but this conjugation is quickly lost upon the addition of a molecule of water, to give the stable neutral molecule (XIV; R = H). The latter is a weaker acid (pK_a 9·7) than the transient neutral molecule, as expected from the structures postulated, and under alkaline conditions the transient anion derived from (XIV; R = H) loses its water of constitution, to form the ion (XVI). Between pH 5·5 and pH 11 the molecule (XVI) and the ion (XIV; R = H) ($+H^+$) attain equilibrium, an equilibrium constant with pK 8·74 being calculated from the variation of the ultraviolet spectrum with pH.

7-Hydroxypteridine.—The ultraviolet absorption spectrum of 7-hydroxypteridine has been shown[4] to be similar to that of a *N*-methyl-7-pteridone, and the latter has been shown[9] to be 8-methyl-7-pteridone (XVII; R = Me). The spectrum of 7-methoxypteridine[12] differs from that of 7-hydroxypteridine, so the latter exists mainly in a



(XVII) (XVIII) (XIX)

pteridone form in aqueous solution. In the solid state 7-hydroxypteridine absorbs strongly in the C:O stretching vibration region (Table 2), whilst the sodium salt and the *O*-methyl derivative do not,[10] indicating that a pteridone form is preferred also in the solid phase.

Of the three possible pteridone forms (XVII—XIX; R = H), the first is the most likely, since the known transannular pteridones (IV and IX; R = R′ = Me) possess ultraviolet spectra which are very different from those of the simple amide pteridones (Figs. 1, 2; Table 1) and are similar in qualitative form to those of the corresponding *N*-methylquinolones (Table 1). The spectra of 1-methyl-7-quinolone and 1-methyl-6-*iso*quinolone, which have conjugated structures similar to those of (XVIII) and (XIX) respectively, show no qualitative resemblance to that of 7-hydroxypteridine, and in view

[11] Bendich and Clements, *Biochem. Biophys. Acta*, 1953, **12**, 462.
[12] Mason, ref. 6, p. 84.

of the close similarity between the spectra of 7-hydroxypteridine and 8-methyl-7-pteridone, the former may be said to exist largely in the form (XVII; R = H).

Experimental

Analyses were done by Mr. P. R. W. Baker, Wellcome Research Laboratories, Beckenham.

Ultraviolet Spectra.—These were measured with a Hilger Uvispek H700/305 Quartz Spectrophotometer. The buffer solutions were 0·01M-glycine (pH 1·5—3·5), 0·01M-acetate (pH 3·8—5·7), 0·01M-phosphate (pH 6·0—7·9 and 10·3—11·3), 0·01M-borate (pH 8·2—10·0), N- (pH 0) and 0·1N-hydrochloric acid (pH 1·0), and 0·1N- (pH 13) and 0·01N-potassium hydroxide (pH 12).

The spectra of the transient neutral molecule and anion of 6-hydroxypteridine were obtained by taking a freshly neutralised solution of the stable anion, or a solution of the stable neutral molecule made freshly alkaline, respectively, for each group of five readings at 5 mμ intervals, each group overlapping by one reading the group before and the group after. For the absorption maxima, fresh solutions were made up for each reading at 1 mμ intervals.

Infrared Spectra.—These were measured with a Perkin–Elmer model 12C spectrometer, incorporating a prism of lithium fluoride for the N–H and O–H stretching vibration region, and a prism of sodium chloride for the C:O stretching vibration region. The compounds were examined as solids included in pressed potassium bromide discs, or in chloroform or carbon tetrachloride solution, 1 cm. or 5 cm. cells respectively being used.

3 : 6 : 7-*Trimethyl-2-pteridone*.[*]—4 : 5-Diamino-1 : 2-dihydro-1-methyl-2-oxopyrimidine[13] (0·7 g.) in boiling water (4 ml.) was mixed with diacetyl (0·5 ml.), and kept at 100° for 5 min. The solid (0·85 g.) was recrystallised from water (40 parts), giving colourless needles of **3 : 6 : 7-*trimethyl-2-pteridone hydrate*** (0·65 g.). It shrinks at ~190° and melts at about 260° (decomp.) (Found, after drying at 120° : C, 51·8; H, 5·6; N, 27·1. $C_9H_{10}ON_4,H_2O$ requires C, 51·9; H, 5·8; N, 26·9%). When the hydrate was thrice recrystallised from ethanol (*ca.* 30 parts) the *ethanolate* was obtained as colourless needles (Found : C, 56·1; H, 6·85; N, 23·8. $C_9H_{10}ON_4,C_2H_5{\cdot}OH$ requires C, 55·9; H, 6·8; N, 23·7%), m. p. 163° on slow heating (lower if heated quickly). Either form, heated above 190° for 10 min., gave insoluble material resembling the product from 3-methyl-2-pteridone (see below).

6 : 7 : 8-*Trimethyl-2-pteridone*.—5-Amino-2-hydroxy-4-methylaminopyrimidine[13] (0·7 g.), water (3 ml.), and diacetyl (0·5 ml.) were kept for 5 min. at 100°. The product (0·9 g.) obtained on chilling recrystallised from water (110 parts) or ethanol (100 parts) as colourless needles of **6 : 7 : 8-*trimethyl-2-pteridone*** (0·75 g.), m. p. 255—260° (decomp.) (dried at 130°) (Found : C, 56·7; H, 5·2; O, 8·6; N, 29·8. $C_9H_{10}ON_4$ requires C, 56·8; H, 5·3; O, 8·4; N, 29·45%). It dissolved in N-sodium hydroxide and at pH 7 was reprecipitated unchanged.

2-Hydroxy-**6 : 7-*dimethylpteridine*.**—Diacetyl (1 ml.) was added to 4 : 5-diamino-2-hydroxypyrimidine (1·25 g.) dissolved in boiling water (13 ml.) and kept on the water-bath for 30 min. After refrigeration, the solid (93%) was recrystallised (carbon) from water (80 parts), to give colourless needles (cf. Daly and Christensen[14]) of 2-hydroxy-6 : 7-dimethylpteridine hydrate, darkening above 200° (Found : C, 49·6; H, 4·7; O, 16·5. Calc. for $C_8H_{10}O_2N_4$: C, 49·5; H, 5·2; O, 16·5%).

Action of Heat on **3-*Methyl-2-pteridone*.**—When kept at 230—240° for 30 min., 3-methyl-2-pteridone[9] gave a light brown residue almost insoluble in boiling water. Although insoluble in toluene or ethanol it was recrystallised from a mixture of these (1 : 1; 50 parts), giving a hygroscopic crystalline *product*, m. p. 285° (decomp.) [Found, for material dried at 150° : C, 51·7; H, 3·85; N, 34·2. $(C_7H_6ON_4)_x$ requires C, 51·85; H, 3·75; N, 34·55%]. Molecular-weight determination was precluded by insolubility in pure solvents, including camphor. It dissolved slowly in warm hydrochloric acid. When it was dissolved in warm 2·5N-sodium hydroxide, and the pH adjusted to *ca.* 6, 3-methyl-2-pteridone hydrate crystallised.

Action of Heat on **1-*Methyl-2-pteridone*.**—When heated at 160—170°, 1-methyl-2-pteridone gave a *product* similar to the above, a white, hygroscopic amorphous powder, m. p. ~200°, from ethanol, insoluble in hot water (Found, for material dried at 110° : N, 32·85. $C_7H_6ON_4,\frac{1}{2}H_2O$ requires N, 32·7%).

6 : 7 : 8-*Trimethyl-4-pteridone*.—Diacetyl (0·25 ml.) was added to a hot solution of 5-amino-4-hydroxy-6-methylaminopyrimidine[13] (0·35 g.) in water (4 ml.). After 5 min. at 100° and chilling, the solid (0·3 g.) was filtered off and recrystallised (carbon) from ethanol (170 parts)

[*] See footnote on p. 3443.

[13] Brown, *J. Appl. Chem.*, 1955, **5**, 358.
[14] Daly and Christensen, *J. Amer. Chem. Soc.*, 1956, **78**, 225.

(or from water), to give yellow needles (0·15 g.) of 6 : 7 : 8-*trimethyl*-4-*pteridone*, m. p. 235—242° (decomp.) (Found, after drying at 120° : C, 56·85; H, 5·4; N, 29·6%). It can be recovered unchanged from its solution in acid or alkali by pH adjustment.

5-Methyl-6-pteridone Monohydrate (7 : 8-*Dihydro*-7-*hydroxy*-5-*methyl*-6-*pteridone*).—Besides by the direct synthesis [9] this compound can be made by heating 5 : 6-dihydro-6 : 7-dihydroxy-5-methylpteridine (0·25 g.) with 2·5N-hydrochloric acid (5 ml.) at 100° for 1 hr. and adjusting the cooled solution to pH 6. The product (0·17 g.) was shown by its spectrum and chromatography to be identical with authentic material.

5 : 6-*Dihydro*-6 : 7-*dihydroxy*-5-*methylpteridine*.—4-Amino-5-methylaminopyrimidine [13] (1 g.) and ethyl glyoxylate ethyl hemiacetal (1·6 ml.) in water (12 ml.) were heated on the water-bath for 40 min. After chilling, the solid was recrystallised from water (80 parts), giving colourless needles (84%) of 5 : 6-*dihydro*-6 : 7-*dihydroxy*-5-*methylpteridine* (dried at 110°), m. p. 251—253° (decomp.) (Found : C, 46·9; H, 4·2; O, 17·9. $C_7H_8O_2N_4$ requires C, 46·7; H, 4·5; O, 17·8%).

7-*Hydroxy*-5-*methyl*-6-*pteridone*.—(a) *By oxidation of* 5 : 6-*dihydro*-6 : 7-*dihydroxy*-5-*methylpteridine*. This substance (0·25 g.) in water (10 ml.) at 60—70° was treated with 5% aqueous potassium permanganate (*ca.* 4·5 ml.) to a persistence of colour. This was discharged by addition of hydrogen peroxide, and the solution filtered and brought to pH ~4. The precipitate was recrystallised from water (45 parts), giving 0·16 g. of colourless 7-*hydroxy*-5-*methyl*-6-*pteridone monohydrate*, m. p. 247—249° (Found : C, 43·0; H, 4·1; N, 28·3. $C_7H_6O_2N_4,H_2O$ requires C, 42·85; H, 4·1; N, 28·55%). The anhydrous *compound* was obtained at about 180° (Found : C, 47·8; H, 3·2. $C_7H_6O_2N_4$ requires C, 47·2; H, 3·4%). Its m. p. was depressed on admixture with starting material.

(b) *By oxidation of* 5-*methyl*-6-*pteridone hydrate*. Oxidation as above gave 0·15 g. of the same product (mixed m. p.; chromatography).

(c) *By direct synthesis*. 4-Amino-5-methylaminopyrimidine [13] (0·25 g.) was heated with diethyl oxalate (2 ml.) for 6 min. at 175—180°. The cooled mixture was diluted with ethanol (0·5 ml.), and the solid filtered off, washed with ethanol (0·5 ml.), and dissolved in water (3 ml.). The solution was made just alkaline with sodium hydroxide and adjusted to pH 3—4 with acetic acid. Refrigeration and recrystallisation gave 0·05 g. of the same product (mixed m. p. and chromatography) as above. When dimethyl oxalate at 140° was used in the above synthesis, a *substance* was formed, crystallising from ethanol (20 parts) in colourless needles, m. p. 179° (decomp.) (Found, after drying at 140° *in vacuo* : C, 44·95; H, 5·4; N, 23·5. $C_9H_{14}O_4N_4$ requires C, 44·65; H, 5·8; N, 23·15%).

1 : 2 : 7 : 8-*Tetrahydro*-3 : 8-*dimethyl*-2 : 7-*dioxopteridine*.—5-Amino-1 : 2-dihydro-1-methyl-4-methylamino-2-oxopyrimidine [13] (0·8 g.) and ethyl glyoxylate ethyl hemiacetal (1·2 ml.) in water (12 ml.) were heated on the steam-bath for 1 hr. Refrigeration, followed by evaporation of mother-liquors to 3 ml., gave in all 0·7 g. of product. It was dissolved in water (110 ml.) and passed through neutral alumina (5 × 2 cm.). The solution was evaporated *in vacuo* to dryness and recrystallised from water (16 parts) (carbon), giving 0·45 g. of bright yellow needles of the *diamide*, m. p. 263° (decomp.), sparingly soluble in hot pentyl alcohol, pyridine, and *iso*butyl methyl ketone (Found : C, 49·85; H, 4·25; N, 29·15. $C_8H_8O_2N_4$ requires C, 50·0; H, 4·2; N, 29·15%).

Permanganate Oxidations.—The hydroxypteridine (0·25 g.) in 0·1N-sodium hydroxide (20 ml.) was treated with 5% potassium permanganate (*ca.* 5 ml.) at room temperature to a permanent coloration. After 20 min. excess of permanganate was destroyed with hydrogen peroxide, and the manganese dioxide filtered or centrifuged off. On adjustment of the filtrate to pH ~4—5, the product crystallised. Hot oxidations were done as for 7-hydroxy-5-methyl-6-pteridone (60—70°) :

Pteridine	Product
2-Hydroxy	2 : 4-Dihydroxypteridine [a] (cold, 72%; hot, 76%)
4-Hydroxy	Unchanged (cold and hot)
6-Hydroxy	6 : 7-Dihydroxypteridine [a] (cold, 65%)
7-Hydroxy	Unchanged (cold); 6 : 7-dihydroxypteridine [b] (hot, 15%)
Unsubst.	4-Hydroxypteridine [a] (cold, 17%)

[a] Identified by infrared spectrum, chromatography, and solubility. [b] No unchanged starting material.

We thank Professor Adrien Albert for helpful discussion and criticism and Mr. E. P. Serjeant for the pH titrations.

Department of Medical Chemistry,
The Australian National University, Canberra. [*Received, March 12th*, 1956.]

668. *The Fluorination of Tellurium. Ditellurium Decafluoride and Tellurium Oxyfluorides.*

By R. Campbell and P. L. Robinson.

The action of fluorine on tellurium gives at ~150° exclusively the hexafluoride, at ~60° hexafluoride and some ditellurium decafluoride, and at ~0° mainly tetrafluoride. The proportion of decafluoride is increased by various solid additives; of these tellurium dioxide was the most effective. Apart from the useful control of temperature brought about by diluting the fluorine with another gas, a gaseous diluent also raises the yield, nitrogen considerably and oxygen much more. With the use of the former the oxyfluoride $Te_2F_{14}O_2$ also appears among the products, and with the latter both this oxyfluoride and a more complex one are formed.

The ditellurium decafluoride has been rigorously purified and many of its properties have been studied. Our data are in substantial agreement with those of English and Dale.[6]

The properties of $Te_2F_{14}O_2$ and the material of higher molecular weight, possibly $Te_6F_{24}O_5$, are described.

At the outset of this investigation (1951) the hexafluoride [1] was the only fluoride of sexavalent tellurium known with certainty. In 1933 Yost and Claussen [2] separated about 1 c.c. of liquid, m. p. −13·6°, b. p. 61·2°, from products of the reaction between tellurium and fluorine, and suggested that it might be ditellurium decafluoride. The evidence was inconclusive and, while working with one of us, Peacock [3] was unable to obtain this liquid in the way prescribed, but from the action of fluorine on tellurium dioxide isolated small quantities of liquid with a range of melting points from −46° to −45° and molecular weights from 351 to 475. The quantities were too small for effective fractionation, but the liquids differed from Yost and Claussen's material in being resistant to water at 100° whereas theirs was decomposed at 85° by heat alone.

Starting from this point the present fluorination of tellurium and its oxides soon showed that, under certain conditions, products containing appreciable quantities of unequivocal decafluoride could be obtained. When notice of a Note on ditellurium decafluoride by English and Dale appeared [4] our work had proceeded so far, and had also disclosed other new compounds, that it was continued.

The broad features of our many preparative experiments are shown in Table 1. Tellurium trioxide yielded only hexafluoride, and the dioxide, which reacts with fluorine at a much lower temperature, gave the same, with a trace of what is either the decafluoride or an oxyfluoride. Tellurium itself at ~150° gives exclusively the hexafluoride; at ~60° this is accompanied by decafluoride in recoverable amounts; and at ~0° the formation of solid tetrafluoride soon prevents further reaction.

Table 1. *Summary of fluorination experiments.*

In furnace	Fluorine, l./hr.	Gaseous diluent, l./hr.	Furnace wall temp., °c.	Products
TeO_3	0·5—10	N_2, 0—5	100—250	Almost entirely TeF_6
TeO_2	0·5—10	N_2, 0—5	100—200	Volatile liquid, trace; remainder TeF_6
Te	2	N_2, 4	40—60	Te_2F_{10}, 5—10%; TeF_6, 80—90%
Te with Al_2O_3, or Ni, or Cu; ratio 1 : 1	3—5	None	60—80	Te_2F_{10}, 10—16%; remainder TeF_6
Te with TeO_2; ratio 1 : 1	3—4	N_2, 10	50—60	Te_2F_{10}, 25%; $Te_2F_{14}O_2$, 2%; remainder TeF_6
Te with TeO_2; ratio 1 : 1	3—4	O_2, 10	50—60	Te_2F_{10}, 40—45%; $Te_2F_{14}O_2$, 5%; higher b. p. material, 0·5%; remainder TeF_6

[1] Prideaux, *J.*, 1906, **322**.
[2] Yost and Claussen, *J. Amer. Chem. Soc.*, 1933, **55**, 885.
[3] Peacock, Ph.D. Thesis, Univ. of Durham, 1951.
[4] *Proc. Chem. Soc.*, 1952, 141.

Mixing the tellurium with solids (*e.g.*, alumina, nickel, copper) and adjusting the fluorine flow rate so as to maintain the reaction tube at ~70° leads to an increased proportion of decafluoride. Mixing with tellurium dioxide and using fluorine alone gives a similar result, but is attended by the production of some oxyfluoride. When, however, the fluorine is diluted with nitrogen the yield of more readily condensable products increases. This increase, consisting mainly of decafluoride, is doubled on changing the diluent from nitrogen to oxygen. The amount of oxyfluoride also rises and a little material of a still higher boiling point appears, which, in consequence, moves little beyond the hot, reaction zone. The proportion of the distinctive products depends in part upon the ratio of dioxide to tellurium, that of the decafluoride and oxyfluoride being increased as this is raised, and also considerably upon the temperature of the reacting charge and the concentration of fluorine. The evidence points to the decafluoride with its linked tellurium atoms being derived from tellurium itself where these atoms are already arranged in spiral chains.[5] That the presence of tellurium oxide and oxygen greatly assists in the production of ditellurium decafluoride may be due to a pre-formation of the high-boiling liquids—undoubtedly oxygen-containing—which, covering the surface of the element, serve as a solvent for the fluorine and so moderate the reaction. In the oxyfluorides we believe the tellurium atoms are separated by oxygen atoms.

We tried the mixture of calcium fluoride and tellurium described by English and Dale,[6] only to produce negligible amounts of the decafluoride, possibly because our diluent was in another form, or we had failed to realise the conditions obtaining in their particular apparatus. The larger amounts of material available and the elaborate purification which we adopted probably account for small differences between the values of some of the physical properties reported by English and Dale and those given here.

Results

Products of Fluorination.—Ditellurium decafluoride. This was charaterised by analysis and molecular weight determination (Found: Te, 57·1; F, 42·6%; *M*, 447 ± 2. Calc. for Te_2F_{10}: Te, 57·3; F, 42·7%; *M*, 445). It is a colourless mobile, stable liquid, unreactive towards water, acids, and alkalis; it was purified by repeated fractional distillation of several large preparations. A summary of the physical measurements we have made is:

d_{25}^{25}, 2·839 g./c.c. (English and Dale give d_{15}^{15} 2·88 g./c.c.).

Density at 273° K, 2·9372 ± 0·0005 g./c.c.; at T° K (range 243—303° K), 4·0984 − 0·00425257T g./c.c.

Coefficient of cubical expansion (range 243—303° K), 0·00145 c.c./c.c./°C.

M. p. −33·7° ± 0·2° C.

B. p. 59° ± 0·2° C/760 mm. (English and Dale give 54°/760 mm.).

Surface tension at 273° K, 17·6 ± 0·2 dynes/cm.; at T° K, γ_T = 49·2 ± 0·2 − 0·11554T dynes/cm.

Viscosity (range −30° to +30° C), 0·01524/(1 + 0·01365t + 0·0000175t^2)P.

Electrical conductivity (range 293—309° K), 3·1 (± 0·4) × 10^{-8} mhos/cm.

The low boiling point suggests a completely covalent compound and there is no evidence of association. The plot of $\gamma(M/\rho)^{\frac{1}{3}}$ against T gives a straight line of slope −3·02, a value rather higher than would be expected for a compound of this molecular weight; its uniformity suggests a normal liquid. A critical temperature of 170° is obtained by extrapolation; this gives a ratio T_b/T_c of 0·75 which is not far removed from the usual 0·6—0·7. The viscosity exhibits no abnormality above −20°, though there is some deviation below that temperature; the plot of fluidity against specific volume is a straight line and the value of w in the Batschinski[7] equation $v = w + c\phi$ (where v is specific volume, ϕ fluidity, and w and c constants) is 0·306, which lies within the usual range for unassociated liquids.

The infrared spectrum is being examined by Mr. R. E. Dodd and the Raman spectrum by Dr. L. A. Woodward; their findings will be published in due course. Specimens, separately prepared and purified, showed identical absorption bands in the infrared region. Very strong absorption has been found at 714, 754, and 888 and strong absorption at 723 and 740 $cm.^{-1}$;

[5] Huggins, *J. Chem. Phys.*, 1945, **13**, 37.
[6] English and Dale, *J.*, 1953, 2498.
[7] Batschinski, *Z. phys. Chem.*, 1913, **84**, 643.

a distribution similar to that found by Gaunt [8] in the spectrum of tellurium hexafluoride where peaks are at 714, 752, and 888 cm.$^{-1}$. The molecule is presumably formed by the linking of two TeF_5 groups; and these, individually, are rather like the hexafluoride molecule and would be expected to absorb at comparable frequencies. The arrangement constitutes a structure well enclosed in a sheath of fluorine atoms. Association of the polar Te–F bonds is likely to be largely prevented by the absence of space for their overlapping. This, along with the size of the molecule which tends to reduce the attractive forces, probably accounts for its monomeric character.

As already mentioned, the decafluoride is not immediately attacked by water or aqueous reagents, but it suffers slow hydrolysis during several months in contact with water, and a crust of fluorotellurates forms on the glass at the fluid interface. The pure, dry liquid has been kept in Pyrex glass for several months without showing evidence of change. It is without noticeable action on iron, copper, and nickel, and, although the vapour causes mercury to tail, the liquid seems to have little effect upon the element. Metallic sodium attacks it at the ordinary temperature with vigour, releasing tellurium and possibly forming polytellurides. Sulphur and selenium are unattacked by the liquid at its boiling point; iodine gives a magenta solution. Neither barium fluoride nor calcium fluoride retains any of the compound after being in the boiling liquid, but sodium fluoride holds some of it tenaciously. The amount is not large, and the *X*-ray diffraction pattern of sodium fluoride proved to be unchanged after 8 hr. under refluxing decafluoride. Presumably any compound formed effectively seals the surface layers of the salts against further penetration.

By contrast with its immiscibility and inertness in aqueous reagents, tellurium decafluoride shows high reactivity towards a wide range of organic compounds. With saturated and halogen-substituted aliphatic hydrocarbons it gives colourless solutions without appreciable reaction or loss of distinctive properties. Mono- and poly-hydric alcohols also produce colourless solutions, sometimes with a noticeable generation of heat, but these solutions no longer show the characteristic reactions of the decafluoride with the organic compounds about to be mentioned. All unsaturated and aromatic hydrocarbons tested become clear yellow. Many substituted aromatic compounds and all amines respond more vigorously, occasionally so violently as to have to be handled in dilute solution. The reactions are complex and may result in the formation of tars, but the solid products sometimes have a remarkable colour : thus catechol, α-naphthylamine, and methyldiphenylamine produce insoluble stable powders respectively green, dark blue, and black.

Tellurium oxyfluorides. We have no evidence of the formation of an oxyfluoride when tellurium, gaseous oxygen, and fluorine are used. In the presence of tellurium dioxide, however, fluorination of tellurium produces a moderate quantity of a liquid b. p. *ca.* 135°. When these conditions are changed by the addition of gaseous oxygen this liquid is accompanied by another in much lower yield and of much higher boiling point. At first we thought that the former was the next member of the sexivalent fluoride series Te_2F_{14}, but the evidence points to their both being oxyfluorides.

Tritellurium dioxotetradecafluoride, $Te_3F_{14}O_2$. This material has been made in lots of up to 10 c.c., and is a colourless mobile liquid, *d* 2·25 ± 0·05 g./c.c. at 20°; m. p. −27°, b. p. 134·5°/755 mm.—its behaviour at these points indicates purity. Analyses show an atomic ratio Te : F of 3 : 14 but account for only 95% of the material; it seems reasonable to suppose that the remainder is oxygen, since the compound is formed only when this element is available. The molecular weight (Dumas's method) is approximately 715 and, for experimental reasons, is probably high. The Table shows that the data are in accordance with the formula suggested.

	Te, %	F, %	O, %	Te/F	*M*		Te, %	F, %	O, %	Te/F	*M*
Te_2F_{14}	59·0	41·0	—	1·44	648·8	$Te_2F_{12}O_2$	58·1	34·6	7·3	1·68	658·8
$Te_3F_{14}O_2$ ...	56·2	39·1	4·7	1·44	680·8	$Te_3F_{10}O_4$	60·1	29·8	10·1	2·02	636·8
Preparation	55·7	38·5	5·8	1·45	715						

The most reasonable structure is an angular one in which the tellurium atoms are separated by oxygen atoms. It may well be that this and the higher-boiling material described below are derived from such units; which may have originated in the dioxide itself since its presence appears to be necessary in the preparation. English and Dale pointed out the very high ratio, molecular weight : boiling point, displayed by tellurium decafluoride, namely 1·36, but in this compound the ratio reaches the remarkable value of 1·67.

[8] Gaunt, *Trans. Faraday Soc.*, 1953, **49**, 1122.

The oxyfluoride distils, without decomposition or attack, in Pyrex glass. Like the decafluoride it is not readily hydrolysed. The liquid has little effect upon mercury but the vapour causes "tailing." Copper, brass, and rubber are unaffected but it dissolves and is absorbed by most greases. "Anhydrone" can be used for drying the liquid which can then be kept in Pyrex glass for long periods without evidence of attack.

Its solubility in and behaviour with organic materials are very similar to those displayed by the decafluoride.

The higher oxyfluoride. Only very small quantities of this material are produced in individual experiments (*ca.* 0·5 c.c.). It is a colourless, mobile liquid which can be kept in Pyrex glass at ordinary temperature. The boiling point seems to be above 300°, but it attacks Pyrex glass long before it boils. That its vapour pressure is very low follows from the fact that it distils exceedingly slowly at 20° under a high vacuum. The density is 3—3·1 g./c.c. at 20°.

Here again analysis for tellurium and fluorine leaves a deficiency of about 7% which is presumably oxygen. The molecular weight is *ca.* 1300. None of our determinations is claimed to be of high accuracy, but we are satisfied that the various values are of the order indicated. The data suggest that if, as we believe, the material is a single compound it should probably be represented by the empirical formula $Te_6F_{26}O_5$.

	Te, %	F, %	O, %	*M*
$Te_5F_{22}O_4$	56·9	37·3	5·8	1120
$Te_6F_{26}O_5$	57·1	36·9	6·0	1340
$Te_7F_{30}O_6$	57·3	36·6	6·2	1559
Preparation	56·6	36·0	7·4	1270, 1300, 1470. Mean 1350

Experimental

Preparation of Sexavalent Tellurium Fluorides.—The reactions summarised in Table 1 were carried out on the solids in nickel tube furnaces connected to a train of Pyrex-glass traps by means of brass unions furnished with neoprene rings. The apparatus was thoroughly dried by repeated evacuation and heating before fluorine, appropriately diluted and previously cooled to −180° to remove condensable impurities, was admitted. The products were condensed at −180° and, after the flow of fluorine was stopped, but before the train of traps was sealed off, the reaction-tube temperature was raised to 150° to allow the nitrogen stream to carry forward the less volatile products. The material thus collected was freed from most of the hexafluoride by keeping it at −60° in one trap connected to another at −180°, the pressure in the system being 10^{-3} mm. Before the trap at −180° was detached, the residue was allowed to warm to −50°. Afterwards it was transferred, in 10 c.c. lots, to an air-cooled reflux column, 23 cm. × 3 mm. fitted throughout its length with a spiral of cupronickel wire (36 s.w.g.), and provided at the head with a thermocouple in a narrow well. Total reflux was maintained for 5 min. to expel hexafluoride after which distillation was allowed to proceed until the take-off temperature became steady. From this point a reflux ratio of about 3 : 1 was maintained and successive fractions boiling at 59° were collected. The apparatus was a closed system thus enabling the fractions to be transferred to break-seal storage bulbs without coming into contact with the air. As soon as the boiling point began to rise the distillate was rejected and this was continued until a second steady boiling temperature of 134° was reached. Excessive reflux, causing the column to flood, was avoided by now surrounding the column with a paper tube. The temperature remained steady at the higher boiling point until the still was empty. Vapour-density measurements on the successive fractions at each of the steady boiling points showed that the materials were uniform and presumably of high purity. A careful examination of the hexafluoride head fraction, made by distilling it in a Podbielniak column, failed to disclose any impurity.

Trap-to-trap distillation, with rigorous temperature control, was also used in the purification of the decafluoride. In some instances the hexafluoride was removed by its selective hydrolysis. For this purpose the crude product was first condensed on ice at −180° and then allowed to warm slowly to room temperature: afterwards the unhydrolysed layer was separated, dried on "Anhydrone," and distilled.

The very high-boiling material collected from the reaction tube itself was not easy to fractionate. At 20°, under a pressure of 10^{-3} mm., it distilled extremely slowly; only 0·5 c.c. of liquid was collected during 6 hr. in a trap immersed in liquid oxygen.

Measurement of the Physical Properties.—For vapour-density measurements, the Dumas method using "Pyrex" bulbs was employed for both Te_2F_{10} and $Te_5F_{14}O_3$. More accurate figures for the decafluoride were obtained by weighing the vapour at 80—100 mm. in bulbs of

30—300 c.c. capacity. The samples were freed from more volatile material as thoroughly as possible, and taps were avoided since grease absorbs the fluoride.

The apparent molecular weight of the very high-boiling product was determined on a modified Victor Meyer apparatus operating at 40—50 mm. and a bulb temperature of 150°. The accuracy was ±8%.

The density of Te_2F_{10} was obtained by use of a calibrated bulb with a capillary stem.

Temp. (°K)	296	289	275·5	261·7	247·5	236·2
Density (g./c.c.)	2·8390	2·8673	2·9255	2·9855	3·0436	3·0916

The surface tension was measured by using two capillary tubes of different, known diameters mounted with the liquid in a sealed vessel.[9]

Temp. (°K)		311	296·2	274·5	258	257
Surface tension (dynes cm.$^{-1}$)	(*a*)	12·94	15·07	17·51	19·25	—
	(*b*)	—	14·85	—	—	19·67

(*a* and *b* refer to different pairs of capillaries.)

The determination of the viscosity has been described elsewhere.[10] The values ranged from 26·66 mP at 14·55° to 11·17 mP at 69·30°.

The cell and the method of measurement used in the determination of conductivity will be described in a later communication.

The infrared spectrum was examined on a Grubb-Parsons S3 single-beam infrared spectrometer, standard technique being used. It was necessary to have the potassium bromide windows of the cell extremely dry; this was effected by keeping them at a pressure of 10^{-4} mm. for a week.

Materials.—Both tellurium and its oxides, derived from AnalaR telluric acid, and also commercial grades of these materials were used without significant difference in result. The fluorine was obtained from a 10 A Imperial Chemical Industries cell. In experiments made without oxygen the halogen stream was run to waste for some time before beginning, and the nitrogen was scrubbed four times with concentrated alkaline pyrogallol.

Analyses.—Tellurium was determined as the element after prolonged reduction of a solution in 1 : 3 hydrochloric acid by means of hydrazine and sulphur dioxide. The fluorine, separated as described by Huckabay, Welch, and Metler,[11] was precipitated and weighed as lead chlorofluoride.

The preparation of solutions suitable for analysis from the tellurium fluorides was difficult. It was achieved by dissolving them in concentrated alcoholic sodium hydroxide containing 10% of pyridine. This solution was then converted into a 1 : 3 hydrochloric acid solution for the determination of tellurium, or used directly in the distillation procedure for fluorine.

The authors are indebted to the United Kingdom Atomic Energy Authority for grants for material and maintenance (R. C.), and to Imperial Chemical Industries Limited, General Chemicals Division, Widnes, for the loan of the fluorine cells used.

KING'S COLLEGE, NEWCASTLE UPON TYNE, 1. [*Received, March 24th*, 1956.]

[9] Mills and Robinson, *J.*, 1927, 1823.
[10] Hetherington and Robinson, *J.*, 1956, in the press.
[11] Huckabay, Welch, and Metler, *Analyt. Chem.*, 1947, **19**, 154.

669. *Nucleotides. Part XXXVIII.* An Improved Synthesis of Uridine-diphosphate-glucose (UDPG).*

By A. M. Michelson and Sir Alexander Todd.

The preparation of 5′-*O*-benzyluridine and of 2′ : 3′-*OO*-dibenzyluridine is described. Condensation of 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphorochloridate with the tri-*n*-octylammonium hydrogen salt of α-D-glucose 1-phosphate in benzene in presence of tri-*n*-butylamine, followed by hydrogenolysis, gives uridine-diphosphate-glucose (UDPG) identical with the natural coenzyme. The crude calcium salt of UDPG isolated directly by precipitation from the hydrogenolysis solution contains about 30% of UDPG and can be used for many biochemical purposes directly. The overall yield of UDPG is *ca.* 15%. Uridine-diphosphate-galactose (UDPGal) can be prepared in similar fashion and in about the same yield.

In Part XXIX of this series [1] a synthesis or uridine-diphosphate-glucose (UDPG) was reported which served to confirm structure (III ; R = H) for this coenzyme. The synthesis which utilised di*cyclo*hexylcarbodi-imide for formation of the pyrophosphate from the pyridinium salts of uridine-5′ phosphate and α-D-glucose 1-phosphate, was unsatisfactory in that the UDPG was formed in low yield as one component of a complex mixture. Indeed it was for this reason that purification of the somewhat unstable UDPG beyond about 40% was not at the time pursued, it being considered wiser to defer further purification until some other method of synthesis suitable for application on a preparative scale could be devised. The classical pyrophosphate synthesis from phosphorochloridates and salts of phosphates [2] has been extended to the synthesis of flavin-adenine dinucleotide (FAD).[3] In that case an *iso*propylidene group was used to protect the 2′- and 3′-hydroxyl groups in the adenosine residue during preparation of the nucleoside phosphorochloridate, and it had to be removed by acid treatment after formation of the pyrophosphate linkage. Since UDPG is more labile than FAD, it was clear that if it were to be synthesised satisfactorily by the phosphorochloridate route the *iso*propylidene group would be unsuitable for protection. The use of benzyl groups seemed a possible alternative since their removal by hydrogenolysis would be unlikely to disrupt the coenzyme molecule. The discovery that the tri-*n*-octylamine hydrogen salt of α-D-glucose-1-phosphate (cf. I) is soluble in benzene therefore made a synthesis of UDPG by condensation of 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphorochloridate (II ; R = $Ph{\cdot}CH_2$) with this salt and subsequent debenzylation an attractive possibility.

O-Benzyl derivatives of nucleosides have not previously been described, but, in the uridine series at least, they are readily prepared. 2′ : 3′-Benzylideneuridine reacts readily when heated with benzyl chloride and potassium hydroxide in dry benzene–dioxan, and removal of the benzylidene group from the product with dilute acid gives 5′-*O*-benzyluridine in good yield. Similar benzylation of 5′-*O*-trityluridine (for which an improved preparation was devised) followed by removal of the trityl residue yielded 2′ : 3′-*OO*-dibenzyluridine. Although palladium oxide and palladised charcoal were ineffective as catalysts, hydrogenation at pH 3—4 in presence of palladium black readily removed the benzyl groups from these nucleoside derivatives.

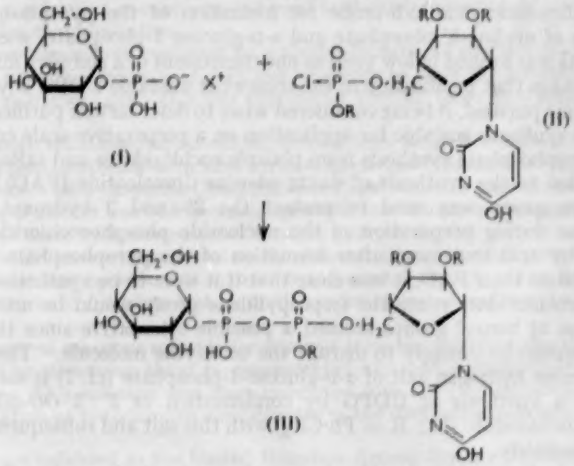
2′ : 3′-*OO*-Dibenzyluridine reacted with *O*-benzylphosphorous *OO*-diphenylphosphoric anhydride to give 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphite, from which *N*-chlorosuccinimide [4] yielded the corresponding phosphorochloridate (II ; R = $Ph{\cdot}CH_2$). The phosphorochloridate was not isolated but was used directly in solution ; there is no doubt of its identity since adding triethylamine to a benzene solution of the phosphorochloridate

* Part XXXVII, *J.*, 1956, 2338.

[1] Kenner, Todd, and Webb, *J.*, 1954, 2843.
[2] Baddiley and Todd, *J.*, 1947, 648.
[3] Christie, Kenner, and Todd, *Nature*, 1952, **170**, 924 ; *J.*, 1954, 46.
[4] Kenner, Todd, and Weymouth, *J.*, 1952, 3675.

and benzyl tri-*n*-octylamine hydrogen phosphate afforded a product which on hydrogenation gave uridine-5′ pyrophosphate (UDP) in good yield.

α-D-Glucose 1-(tri-*n*-octylamine hydrogen phosphate), like 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphorochloridate, is soluble in dry benzene. When triethylamine was added to a benzene solution of both substances, reaction occurred but there was also a good deal of precipitation of sugar phosphate salt: this precipitation was avoided by using tri-*n*-butylamine instead of triethylamine. The reaction product was first hydrogenated on a palladium oxide–palladised charcoal catalyst to remove the benzyl ester residue from the pyrophosphate linkage. Long-chain amines (together with any tetrabenzyl diuridine-5′ pyrophosphate which may have been formed) were then removed by addition of triethylamine to an aqueous-ethanolic solution of the product and extraction with chloroform. Hydrogenation of the crude 2′ : 3′-dibenzyl ether of UDPG in aqueous ethanol in the presence of palladium black then gave a product which was precipitated as a calcium salt. This crude calcium salt [0·9 g. from 1·125 g. of α-D-glucose 1-(potassium hydrogen phosphate)] was suitable for most biochemical purposes without further purification; about 50% of the uridine present in it was in the form of UDPG, the remainder being mainly uridine-5′ phosphate. On a weight basis it contained *ca.* 30% of the calcium salt



of UDPG and contained as other impurities glucose 1-phosphate and two other glucose derivatives, one of which was probably the cyclic 1 : 2-phosphate; the overall yield was therefore *ca.* 15%, but this could probably be improved by further study of reaction conditions. By further purification the calcium salt of UDPG (III; R = H) was isolated in effectively pure condition (92% by enzymic assay).

The synthetic method described is probably generally applicable to the synthesis of uridine-diphosphate-sugar derivatives. When α-D-galactose 1-phosphate was substituted for glucose 1-phosphate, uridine-diphosphate-galactose (UDPGal)[5] was also obtained in *ca.* 15% yield; it was isolated as a calcium salt but was not purified beyond 48% (enzymic assay). In view of the difficulty of obtaining such compounds in quantity and free from each other from natural sources, these syntheses might well serve as a preparative method for UDPG, UDPGal, and by analogy for other UDP-sugar and UDP-uronic acid derivatives of biochemical interest.

Since it has been shown that acetyl groups can be removed from nucleoside derivatives under extremely mild conditions [6] a synthesis of UDPG using 2′ : 3′-*OO*-diacetyluridine-5′ benzyl phosphorochloridate was attempted. Hydrogenolysis of the

[5] Leloir, *Arch. Biochem.*, 1951, **33**, 186.
[6] Michelson, Szabo, and Todd, *J.*, 1956, 1546.

product followed by carefully controlled alkaline deacetylation did in fact give UDPG. The yield, however, was only about 5% and the crude calcium salt obtained directly from the reaction had only about 10% of its uridine content as UDPG.

Experimental

Aniline Hydrogen Phthalate Reagent.—In order that it could be used directly for the detection of glucose 1-phosphate and its derivatives without prior hydrolysis, hydrochloric acid was added to the reagent solution as described by Partridge [7] until it was 0·07N with respect to hydrochloric acid. Paper chromatograms were sprayed with this modified reagent and heated to 105° for 10 min. to develop the spots.

5′-O-*Benzyluridine.*—Benzyl chloride (6 c.c.) was added to a suspension of 2′ : 3′-*O*-benzylidene uridine [8] (6·25 g.) and powdered potassium hydroxide (25 g.) in dry benzene (70 c.c.) and dry dioxan (20 c.c.), and the mixture refluxed with vigorous stirring during 5 hr., then cooled. Water (200 c.c.) was added, followed by glacial acetic acid to neutrality (pH 7). The benzene layer was separated, washed with water, dried (Na_2SO_4), and evaporated under reduced pressure, residual benzyl chloride being removed in a high vacuum. The residue was dissolved in ethanol (60 c.c.), and 0·2N-aqueous hydrochloric acid (40 c.c.) was added, giving a solution of 0·08N-acidity, which was refluxed for 1½ hr., then concentrated to half bulk. The cooled solution was neutralised with aqueous potassium hydrogen carbonate and thrice extracted with chloroform. The combined chloroform extracts were washed, dried (Na_2SO_4), and evaporated and the residue triturated with light petroleum until it crystallised. Recrystallised from acetone–light petroleum (b. p. 40—60°), 5′-O-*benzyluridine* formed colourless prisms (3·1 g.), m. p. 162° (Found, in material dried at 100°/10^{-3} mm. for 6 hr.: C, 57·8; H, 5·7; N, 8·4. $C_{16}H_{16}O_6N_2$ requires C, 57·5; H, 5·4; N, 8·4%).

5′-O-*Trityluridine* (*cf. Levene and Tipson* [9]).—A solution of anhydrous uridine (22 g.) and triphenylmethyl chloride (26 g.) in dry pyridine (250 c.c.) was set aside at room temperature for 2 days and then heated on a boiling-water bath for 2 hr. with exclusion of moisture. The solution was cooled and poured into ice-water (150 c.c.) with vigorous stirring, the precipitated gum washed with water and dissolved in acetone, and the solution filtered and evaporated to dryness, the last traces of pyridine being removed in a high vacuum. The residue was dissolved in warm benzene (100 c.c.), and the solution seeded and allowed to cool; 5′-*O*-trityluridine (36 g., 81%) separated as colourless crystals, m. p. 200°.

2′ : 3′-*OO*-*Dibenzyluridine.*—Powdered potassium hydroxide (100 g.) was added to a solution of 5′-*O*-trityluridine (34 g.) in dry benzene (200 c.c.)–dioxan (75 c.c.) containing benzyl chloride (47 c.c.), and the mixture was refluxed with stirring for 4½ hr. The fine suspension was decanted from the heavier excess of potassium hydroxide which was washed with more benzene. Water and acetic acid were added to the combined benzene suspension and washings until pH 7 was reached. The benzene layer was washed with water, dried (Na_2SO_4), and evaporated under reduced pressure. The gummy residue was washed with light petroleum (b. p. 40—60°) and dissolved in aqueous acetic acid (300 c.c. of 80%), and the solution refluxed for 10 min. and then evaporated to dryness. The residue was shaken thoroughly with ether–light petroleum to remove triphenylmethanol, then rubbed with a little ether until it crystallised. Recrystallised from acetone–heptane or aqueous ethanol 2′ : 3′-*OO*-*dibenzyluridine* formed colourless needles (20 g., 70%), m. p. 147° (Found, in material dried at 70°/1 mm. for 6 hr.: C, 65·5; H, 5·9; N, 6·6. $C_{23}H_{24}O_6N_2$ requires C, 65·1; H, 5·7; N, 6·6%).

2′ : 3′-*OO*-*Dibenzyluridine*-5′ *Benzyl Phosphorochloridate.*—A solution of 2′ : 3′-*OO*-dibenzyluridine (1 g.) in dry benzene (25 c.c.) was added to *O*-benzylphosphorous *OO*-diphenylphosphoric anhydride (from 0·81 g. of benzyl dihydrogen phosphite [10]) in benzene (20 c.c.), followed by 2 : 6-lutidine (0·54 c.c.), and the mixture set aside at room temperature overnight. The benzene solution was then washed with water, aqueous sodium hydrogen carbonate, aqueous potassium hydrogen sulphate, and water, and dried (Na_2SO_4). Solvent was removed under reduced pressure and the residue precipitated twice by addition of *n*-heptane to a concentrated benzene solution. The final precipitate of 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphite was dried over phosphoric oxide *in vacuo* (1·21 g., 86%). The phosphorochloridate was prepared by treating a solution of the phosphite (2·34 g.) in benzene (15 c.c.) with *N*-chlorosuccinimide (0·55 g.) at room temperature during 2 hr. and was used directly without isolation.

[7] Partridge, *Nature*, 1949, **164**, 443.
[8] Gulland and Smith, *J.*, 1947, 338; *cf.* Brown, Haynes, and Todd, *J.*, 1950, 2299.
[9] Levene and Tipson, *J. Biol. Chem.*, 1934, **104**, 385.
[10] Corby, Kenner, and Todd, *J.*, 1952, 3669.

α-D-*Glucose* 1-(*Tri*-n-*octylammonium Hydrogen Phosphate*).—An aqueous solution of α-D-glucose 1-(dipotassium phosphate) (1·125 g. of dihydrate, 1 mol.) was passed through a column of IR-120 resin (acid form), and the solution of the free acid so obtained was added to an ethanolic solution of tri-*n*-octylamine (1·08 g., 1 mol). Water was removed azeotropically by distillation with ethanol–benzene, and the resultant solution was evaporated to dryness. The residue was repeatedly re-evaporated with toluene to remove any remaining traces of water, and the glassy salt stored over phosphoric oxide.

Uridine-diphosphate-glucose (*UDPG*).—The above monotri-*n*-octylammonium salt (from 1·125 g. of potassium salt, 1 mol.) in dry benzene (15 c.c.) was added to a solution of 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphorochloridate (from 2·34 g., 1·34 mols., of the phosphite) in dry benzene (15 c.c.). To the stirred mixture tri-*n*-butylamine (0·76 g., 1·34 mols.) in dry benzene (15 c.c.) was added during 30 min., moisture being rigorously excluded. Stirring was continued for a further 1½ hr. at room temperature, then solvent was evaporated under reduced pressure. The residue was vigorously shaken with *n*-heptane (100 c.c.), the solvent decanted, and the precipitate washed with *n*-heptane by decantation, dried quickly *in vacuo*, and dissolved in 90% ethanol (70 c.c.). This solution was shaken with hydrogen and palladium oxide–palladised charcoal at room temperature and atmospheric pressure; hydrogen uptake for removal of one benzyl group was complete in 3 hr. Catalyst was filtered off and the filtrate brought to pH 7 with triethylamine and concentrated to *ca.* 40 c.c. under reduced pressure. Water (20 c.c.) was then added and the solution was extracted with chloroform, triethylamine being added cautiously with shaking after each addition, until the aqueous layer was permanently at pH 7·4. (The chloroform layer was tested for glucose-containing material and if necessary was further extracted with aqueous triethylamine.) The chloroform extracts containing long-chain amine and glucose-free dinucleotide pyrophosphate were discarded. The aqueous layer was concentrated to *ca.* 40 c.c. under reduced pressure, ethanol (40 c.c.) was added, and the pH adjusted to pH 3·6 with glacial acetic acid. Palladium black (*ca.* 1 g.) was added and the mixture shaken with hydrogen until removal of benzyl groups was complete (checked by paper chromatography) in 12—24 hr. Catalyst was removed, and the filtrate adjusted to pH 7·1 with triethylamine and concentrated to 10—20 c.c. under reduced pressure. Acetone (200 c.c.) was added and the resulting precipitate of crude triethylammonium salt was collected and its solution in aqueous ethanol (40 c.c. of 60%) was filtered and treated with calcium chloride (0·75 g.) in ethanol (40 c.c.). The white precipitate of the crude calcium salt of UDPG was collected by centrifugation, washed with ethanol and ether, and dried (0·90 g.). Enzymic analysis showed that *ca.* 50% of the ultraviolet absorption of this salt was due to UDPG. Paper chromatography showed in addition to UDPG mainly uridine-5′ phosphate with benzylated material and a trace of uridine-5′ pyrophosphate, as ultraviolet-absorbing components.

The above crude calcium salt (50 mg.) was run on a paper chromatogram [descending; ethanol–M-ammonium acetate (7 : 3); Whatman 3MM paper 44 × 22 cm.; 48 hr.]. The appropriate band was eluted, its solution concentrated to 0·3 c.c., and the ammonium salt of UDPG precipitated with acetone (20 c.c.). Enzymic analysis [11] showed a purity of 92%. The ammonium salt was dissolved in aqueous ethanol (80%), and ethanolic calcium chloride added. The precipitated *calcium uridine-diphosphate-glucose* was completely homogeneous when examined by paper chromatography in several solvent systems and by paper electrophoresis and was indistinguishable from a sample of UDPG of natural origin [Found: in material dried at 110°/10^{-3} mm. for 12 hr.: P, 10·4; ratio P/uracil (spectroscopically), 1·9/1; ratio glucose (Somogyi [12])/uracil, 1·07/1. $C_{15}H_{22}O_{17}N_2P_2Ca$ requires P, 10·3%; ratio P/uracil, 2/1; ratio glucose/uracil, 1/1].

Uridine-diphosphate-glucose from 2′ : 3′-OO-*Diacetyluridine-5′ Benzyl Phosphorochloridate*.—The above preparation was repeated with the differences that 2′ : 3′-*OO*-diacetyluridine-5′ benzyl phosphorochloridate [13] (prepared by the usual method in benzene–acetonitrile) was substituted for the dibenzyl compound and the second hydrogenolysis was omitted. Acetyl groups were removed by treatment with aqueous triethylamine at pH 9·4 for 24 hr. at room temperature. The crude calcium salt [1·4 g. from 1·4 g. of glucose 1-(dipotassium phosphate)] was shown by enzymic assay to have 11% of the uridine present in the form of UDPG. One-step purification by paper chromatography and conversion of the ammonium into the barium salt gave a product which contained 30% of UDPG by chemical and 32% by enzymic assay.

[11] Strominger, Kalckar, Axelrod, and Maxwell, *J. Amer. Chem. Soc.*, 1954, **76**, 6411.
[12] Somogyi, *J. Biol. Chem.*, 1951, **195**, 19.
[13] Kenner, Todd, Webb, and Weymouth, *J.*, 1954, 2288.

Uridine-diphosphate-galactose (*UDPGal*).—The dipotassium salt of α-D-galactose 1-phosphate (0·6 g. dihydrate, 1 mol.) was converted into the monotri-*n*-octylammonium salt as described above for the glucose derivative and condensed with 2′ : 3′-*OO*-dibenzyluridine-5′ benzyl phosphorochloridate (from 1·13 g., 1·4 mols. of phosphite) in dry benzene with tri-*n*-butylamine. The reaction procedure and working up were as described above for UDPG. The crude calcium salt (0·675 g.) of UDPGal obtained by direct precipitation, contained UDPGal corresponding to some 35% of the ultraviolet absorption by enzymic assay. One-stage purification by paper chromatography gave material containing approx. 50% of the coenzyme by enzymic assay.

Paper Chromatography.—Ascending chromatograms run for 24 hr on Whatman No. 1 paper, with ethanol–M-ammonium acetate (7 : 3) as solvent, gave R_{uridine}: uridine-5′ phosphate, 0·29; uridine-5′ pyrophosphate (UDP), 0·10; diuridine-5′ pyrophosphate, 0·13; UDPG (natural and synthetic) 0·41; UDPGal (synthetic), 0·40; α-D-glucose 1-phosphate, 0·34; α-D-galactose 1-phosphate, 0·335. In ethanol–M-acetic acid (75 : 30) with ammonia to pH 3·8, UDPG (natural and synthetic) had the $R_{\text{adenosine}}$ previously reported.[1]

We gratefully acknowledge grants from the Rockefeller Foundation and Roche Products Ltd. and a gift of α-D-glucose 1-phosphate from Dr. J. L. Strominger. We are also deeply indebted to Drs. Agnete Münch-Petersen and J. L. Strominger for their kindness in carrying out enzymic assays on our synthetic materials.

UNIVERSITY CHEMICAL LABORATORY, CAMBRIDGE. [*Received, March 28th*, 1956.]

---

670. *Dielectric Properties of Some Aluminium Soaps and of their Solutions in Toluene.*

By S. M. NELSON, A. GILMOUR, and R. C. PINK.

In dilute toluene solutions of aluminium disoaps, the dielectric loss is due almost entirely to direct-current conductivity. In more concentrated solutions, which form rigid gels, part of the dielectric loss is caused by the restricted displacement and accumulation of ions along internal boundaries in the gel. In solutions of the aluminium trisoaps, in which aggregation is limited to the dimer, the dielectric loss is due solely to direct-current conductivity. The stability of the ions in a solvent of such low dielectric constant as toluene is explained by the shielding effect of the hydrocarbon chains which prevents close approach of the ionic charges localised in the centre of the aggregates.

IN a previous paper [1] it was shown that the dielectric loss in hydrocarbon solutions of a number of bivalent metal soaps was due to direct-current conductivity. The variations in the conductivity of these solutions with changes in concentration and temperature were explained in terms of an association of molecules and ions into aggregates, the equivalent conductivity increasing with increase in aggregate size. In certain calcium oleate solutions, however, which were highly viscous, it was noted that the measured dielectric loss contained a component due to some cause other than ionic conduction.

The present paper describes an investigation of the dielectric properties of some aluminium soap solutions in toluene in which a similar phenomenon has been observed. Unlike the bivalent metal carboxylates, the aluminium disoaps in hydrocarbon solvents form viscoelastic gels even at low concentrations and it was expected that a study of the dielectric properties of the soaps might help to elucidate the nature of this gel structure.

EXPERIMENTAL

Preparation and Purification of Materials.—Aluminium dilaurate was prepared by the method described by Smith, Pomeroy, McGee, and Mysels.[2] The soap was washed free from

[1] Nelson and Pink, *J.*, 1954, 4412.
[2] Smith, Pomeroy, McGee, and Mysels, *J. Amer. Chem. Soc.*, 1948, **70**, 1053.

chloride and then extracted with dioxan at 40° until free from uncombined fatty acid. After the soap had been dried, traces of dioxan were removed at low pressure. The trilaurate and trioleate were prepared by Mehrotra's method.[3]

Analytical data (Al) for two samples of each of these three soaps are—Dilaurate: Found: 6·22, 6·19. Calc.: 6·09. Trilaurate: Found: 4·25, 4·27. Calc.: 4·32. Trioleate: Found: 3·12, 3·23. Calc.: 3·10%.

Preparation of the Gels.—In order to exclude moisture, the aluminium dilaurate gels were prepared under a slight positive pressure of dry air at 40—60° with mechanical stirring. Under these conditions the soap swelled rapidly, forming first a viscous suspension of undispersed soap and, finally, a transparent gel. Stirring was continued for 10 min. after the system had become visibly homogeneous. In the peptised systems the peptiser was added with the solvent.

Apparatus.—Dielectric-loss measurements in the frequency range 100 cycles/sec. to 300 kcycles/sec. were made with the capacitance bridge described previously.[1] Measurements in the range 100 kcycles/sec. to 40 megacycles/sec. were made by the method due to Hartshorn and Ward [4] involving variation of reactance in a tuned circuit. The dielectric cells were similar to those employed previously.

Where relaxation effects are absent in the dielectric, and the whole of the dielectric loss is due to direct-current conduction, it can be shown from a consideration of the voltage–current vectors that the dielectric loss factor ϵ'' is inversely proportional to frequency. The specific conductance σ can then be calculated from eqn. (1),

$$\sigma = 5{\cdot}5 \times 10^{-12}\epsilon'' f \text{ ohm}^{-1} \text{ cm.}^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where f = frequency in cycles/sec.

The conductivity in some of the systems was also measured directly by applying 1·5 v across the sample in the dielectric cell and observing the current by a sensitve galvanometer (6000 mm./μA at 1 metre) calibrated by means of known high resistances. To reduce electrode polarisation effects, a reversing switch was employed to change the direction of the current flow through the cell, but not through the galvanometer, at the rate of one reversal every 2 sec. With systems in which the whole of the loss was due to direct current conductivity, the two methods showed excellent agreement.

Results

Fig. 1 illustrates the frequency dependence of the dielectric loss for aluminium dilaurate gels in toluene at three concentrations at 25° over a wide frequency range. The data refer to the systems after they had matured for at least 2 days and had acquired constant loss values. It will be seen that the two most concentrated systems show a considerable departure from a conductivity plot (*i.e.*, $\epsilon'' \propto 1/f$ corresponding to the broken line in Figs. 1 and 2), approaching the 45° slope required by direct-current conductivity below 500 cycles/sec. Direct measurement of conductance confirmed that the loss below this frequency was almost entirely due to direct-current conductivity. Specific conductivities measured by the direct method (i) and calculated from the loss data at the lowest frequency of measurement (ii) are shown in the Table.

Specific conductivity of aluminium dilaurate in toluene.

Concn. (g./100 ml. of soln.)	0·44	2·52	4·86
Specific conductivity (10^{10} ohm^{-1} cm.$^{-1}$), method (i)	1·61	0·805	1·02
" " " method (ii)	1·61	0·887	1·17

Effect of Peptising Agents.—Fig. 2 illustrates the effect of lauric acid as peptiser on the dielectric loss of the 2·52% aluminium dilaurate gel at 25°. The effect of lauric acid on the mechanical properties of the gel was to render it less friable and more elastic. From Fig. 2 it is clear that peptising action is also accompanied by an increase in conductivity and by a change in the shape of the log ϵ''–log f curves, the departure from a conductivity slope of 45° becoming less apparent. Lauric acid in amounts greater than 1 mol. had no further significant effect on the dielectric properties.

Effect of Temperature.—The dielectric losses of the unpeptised and the peptised gels were measured at 40°. In all cases a small increase in the dielectric loss (*ca.* 5—10%) on the values at 25° was observed.

[3] Mehrotra, *Nature*, 1953, **172**, 74.
[4] Hartshorn and Ward, *J. Inst. Elect. Engrs.*, 1936, **79**, 597.

Analysis of the ε″–f Curves.—Where the loss factor due to direct-current conductance represents only a part of the total loss, the observed loss factor may be regarded as the sum of two distinct effects :[5]

$$\varepsilon''_{obs.} = \varepsilon''_{d.c.} + \varepsilon''_{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $\varepsilon''_{d.c.}$ is given by eqn. (1) above and ε''_{r} is the dielectric loss resulting from relaxation phenomena involving dipoles or ions. ε''_{r} may then be obtained provided the direct-current conductivity is measured separately. In Fig. 3 the dielectric data for a 2·52% aluminium dilaurate gel are analysed in this way. The direct-current conductivity losses calculated from the measured conductivity are shown by the broken curve. On plotting $\varepsilon''_{obs.} - \varepsilon''_{d.c.}$ on the same co-ordinates, a maximum is obtained in the region of 10 kcycles/sec. Fig. 4 shows plots of $\varepsilon''_{obs.} - \varepsilon''_{d.c.}$ against log f for the three unpeptised gels at 25°. In addition to causing an increased loss, increase in concentration of the gel also leads to a small decrease in the frequency of maximum absorption. The errors in the results of Fig. 4 are large (±10%), because they were obtained from the difference of measured quantities.

Fig. 1. Fig. 2.

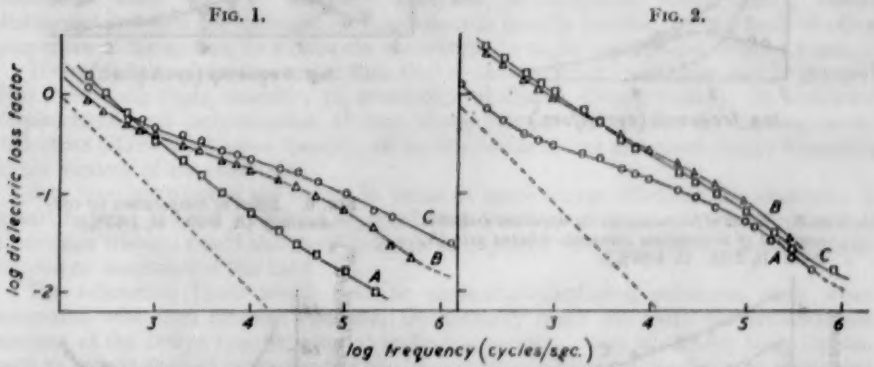


Fig. 1. *Effect of frequency on dielectric loss of aluminium dilaurate gels* (A, 0·44; B, 2·52; C, 4·86%).
Fig. 2. *Effect of peptiser on dielectric loss of an aluminium dilaurate gel* (2·52%) *in toluene* (A, *unpeptised gel*; B, 0·398 *mol. of lauric acid*; C, 1·06 *mol. of lauric acid*).

Dielectric Constant.—In all the aluminium disoap systems the measured capacitance was observed to decrease with increasing frequency (Fig. 5). The increase in capacitance at low frequencies observed in the 0·44% system, which was almost wholly conducting, may be explained largely by electrode polarisation.

The Aluminium Trisoaps.—Solutions of aluminium trilaurate and trioleate in toluene were found to have high dielectric losses, which in every case varied inversely with frequency, indicating that the losses were due to direct-current conductivity. The specific conductivity calculated from the loss data for solutions of aluminium trilaurate in toluene are shown in the Table, while the effect of temperature on the conductivity is shown in Fig. 6.

Aluminium trilaurate, %	0·853	0·990	1·630	2·204	2·65
Specific conductivity, 10^{10} ohm^{-1} cm.$^{-1}$ ...	1·64	3·07	14·50	34·05	74·90

The conductivities observed in these solutions cannot be accounted for simply by the presence of free fatty acid or water, since even concentrated solutions of fatty acids in toluene show a negligible increase in dielectric loss over that of the pure solvent, while in the case of the trisoaps addition of a trace of water leads to a marked fall in conductivity as a result of hydrolysis to the aluminium disoap.

Dielectric Properties of the Solid Soaps.—The dielectric loss of the solid disoaps was found to be very low, provided care was taken to extract free fatty acid and to prevent absorption of moisture by the soap sample. Solid aluminium trilaurate, in contrast, showed large losses at low frequencies with a marked dependence of the dielectric loss on frequency, as illustrated in Fig. 7, which includes the loss data for the disoap. It will be seen that the loss for the disoap passes through a shallow maximum at a frequency of about 1 megacycle/sec.

[5] Carter, Magat, Schneider, and Smyth, *Trans. Faraday Soc.*, 1946, **42**, *A*, 213.

FIG. 3. *Analysis of dielectric loss of an aluminium dilaurate gel in toluene* ($\sigma_{D.C.} = 0{\cdot}805 \times 10^{-10}$ ohm^{-1} cm.$^{-1}$) (A, $\varepsilon''_{obs.}$; B, $\varepsilon''_{d.c.}$; C, $\varepsilon''_{obs.} - \varepsilon''_{d.c.}$).

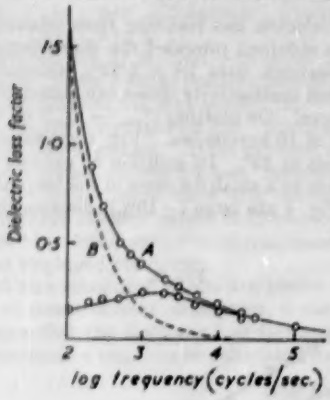


FIG. 4. *Dielectric absorption of aluminium dilaurate–toluene gels* (A, 0·44; B, 2·52; C, 4·86%).

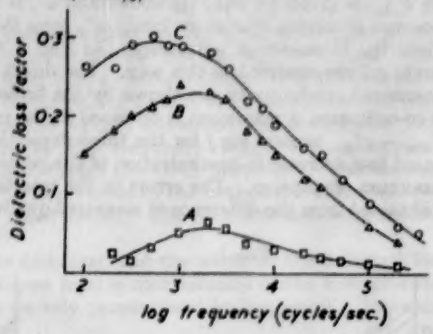


FIG. 5. *Effect of frequency on the apparent dielectric constant of aluminium dilaurate–toluene gels* (A, 0·44; B, 2·52; C, 4·86%).

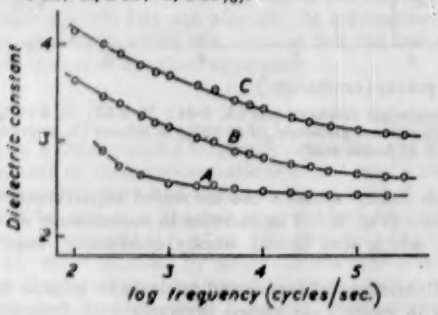
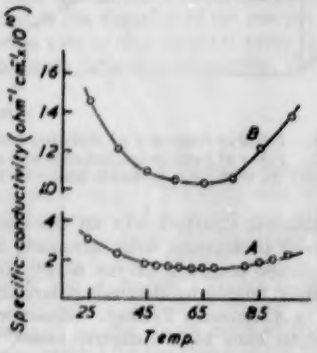


FIG. 6. *Effect of temperature on conductivity* (A, 0·99; B, 1·63%).



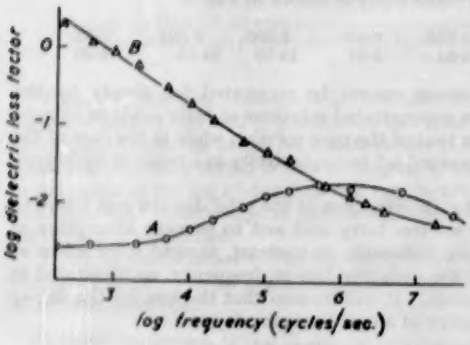


FIG. 7. *Effect of frequency on dielectric loss of aluminium dilaurate* (A) *and aluminium trilaurate* (B).

Discussion

Like the solutions of bivalent metal soaps, the aluminium soap gels show appreciable direct-current conductivity. An important difference, however, is that in the former the dielectric loss can be entirely accounted for by direct-current conduction, while in the gels, a component of the loss is due to some other cause. This component increases in magnitude, and the frequency at which it shows a maximum is lowered, with increase in concentration of the soap (Fig. 4).

Various theories of dielectric absorption have been proposed to account for power loss in alternating fields.[7] Most of the proposed mechanisms, however, lead to the same kind of formal expression [eqn. (3)] for the variation of loss factor with frequency

$$\epsilon'' = A\omega\tau/(1 + \omega^2\tau^2) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where A is a constant, ω is the angular frequency, and τ is the time constant or relaxation time for the process in question. It is clear from this equation that ϵ'' passes through a maximum when $\omega\tau = 1$. Although electrical measurements alone cannot always distinguish between the different mechanisms it is usually possible, on the basis of other properties of the system, to ascribe the absorption, in major part, to one or other cause.

Dielectric-loss mechanisms other than that of direct-current conduction may be grouped into three main types, namely: (1) orientation of dipoles (Debye theory); (2) restricted displacement and accumulation of ions along internal boundaries in inhomogeneous dielectrics (Maxwell–Wagner theory); (3) accumulation of ions and space charge formation in the vicinity of the electrodes.

Any interpretation of the results in terms of space charge effects at the electrodes is unsatisfactory, since it would be expected that solutions of bivalent metal oleates and aluminium trisoaps would also show dielectric absorption. On the contrary, these solutions showed no anomalies of this kind.

The relaxation times which describe molecular-orientation processes, even when associated with high internal viscosity, are normally much too small for dielectric-loss maxima of the Debye type to occur at audio-frequencies. Only when very large dipoles, such as certain protein molecules [8] or the co-operative rotation of dipoles as in long-chain alcohols [9] are encountered, are the relaxation times sufficiently large to produce an audio-frequency response. Although very large aggregates are known to exist in aluminium soap gels,[10] rotation of such aggregates as a whole is unlikely, since they possess no net dipole moment.

In view of the large part played by direct-current conduction, a possible account of the audio-frequency dielectric loss may be found in terms of restricted movement of ions. It is significant that the dielectric absorption is observed only for systems of high viscosity where a non-uniform conductance path might be expected. Following this argument, a mechanism based on Maxwell–Wagner theory is proposed here to account, qualitatively, for the dielectric absorption in aluminium soap gels.

Evidence exists that aluminium soap gels in hydrocarbon solvents comprise a more or less random arrangement of long chains of soap molecules.[11] The aggregation of soap molecules to the extent necessary to produce gelation would lower the electrical conductivity in two ways. First, the mobility of the charge-carriers, which themselves are probably bulky, would be greatly reduced because of the high viscosity and, secondly, a proportion of the charged micelles would be effectively immobilised by actual incorporation into the chains. This is reflected in the dielectric-loss results for aluminium dilaurate

[6] Debye, *Verh. deutsch. physik. Ges.*, 1913, **15**, 777; Maxwell, "Electricity and Magnetism," Oxford Univ. Press, 1928; Wagner, *Archiv Electrotecnik*, 1914, **2**, 371; Murphy and Lowry, *J. Phys. Chem.*, 1930, **34**, 598; Whitehead and Marvin, *Trans. Amer. Inst. Elect. Engrs.*, 1929, **48**, 313; see, Manning and Bell, *Rev. Mod. Phys.*, 1940, **12**, 215, for other references.

[7] Oncley, *Chem. Rev.*, 1942, **30**, 433.

[8] Meakins and Welsh, *Austral. J. Sci. Res.*, 1951, *A*, **4**, 359.

[9] Gray and Alexander, *J. Phys. Colloid Chem.*, 1949, **53**, 23; McBain and Working, *ibid.*, 1947, **51**, 974.

[10] Gray and Alexander, ref. 9; McGee, *J. Amer. Chem. Soc.*, 1949, **71**, 278; McBain and Working, ref. 9.

[11] Cf. Murphy and Lowry, ref. 6.

in toluene (Fig. 1) where the more dilute systems are more conducting than the concentrated rigid gels.

In addition to increasing the resistance to motion of charged particles, gelation would also render the conductance path non-uniform. This is to be expected in a gel structure where the ions are large and would result in an accumulation of charge-carriers at points in the structure where there are steric barriers to their movement. The restricted displacement and accumulation of ions in this way is equivalent to a condenser charging current, and their return to an equilibrium distribution, to a discharge current. Thus, the conductance path, instead of being represented by a pure resistance is now represented by a resistance in series with a capacity.[12] The ionic accumulations, which may properly be regarded as equivalent to a dielectric polarisation, would make a contribution to the measured capacity of the sample. The charge q at time t after the application of a direct potential V to a capacity C_1 in series with resistance R_1 is given by eqn. (4). The time

$$q = C_1V[1 - \exp(-t/C_1R_1)] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

constant for the charging process is equal to C_1R_1. In alternating fields the equivalent parallel capacity of this net work C_p varies with frequency according to eqn. (5) thus

$$C_p = C_1/[1 + (C_1R_1\omega)^2] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

accounting for the decrease in apparent dielectric constant with increasing frequency observed for the aluminium soap gels (Fig. 5). The frequency at which the dielectric absorption shows a maximum is determined by the value of C_1R_1 in eqn. (3), and the actual variation of loss factor with frequency is given by substitution of this value in eqn. (2). These equations refer to the simplest hypothetical case, however, and since it would be expected that the ionic accumulations would be described by a distribution of relaxation times instead of only one, a large number of different values of capacity and resistance, C_1R_1, C_2R_2, ... C_nR_n, must be assumed.

Effect of Peptisers.—The effect of lauric acid in concentrations up to 1 mol. is to increase the direct-current conductivity and to decrease the component of the loss due to absorption as judged by the slope of the log ε''–log f curves (Fig. 2). These trends may be interpreted in terms of a less ordered and more homogeneous structure in which the conduction path is less resistive and more uniform. Such a change in structure would be brought about by a decrease in the average chain-length of the soap aggregates. This picture is consistent with the peptisation mechanism proposed by Gray and Alexander [10] in which the peptiser molecules are preferentially co-ordinated to the aluminium atoms, thus saturating the forces which would otherwise hold the soap molecules together.

The Aluminium Trisoaps.—Unlike the disoaps, aluminium trilaurate dissolves in hydrocarbons to give mobile solutions in which ebullioscopic measurements have shown that the trilaurate is molecularly dispersed. Even in concentrated solutions, aggregation does not proceed beyond the dimer. The explanation of this limited aggregation, which is in strong contrast to the behaviour of the aluminium disoaps, lies primarily in the absence of the hydroxyl group and possibly also in the steric hindrance to further aggregation which is provided by the six hydrocarbon chains of the dimer.

In the absence of any restriction on the movement of ions similar to that provided by the gel structure in the case of the disoaps, it would be expected that the dielectric loss in the trisoap solutions might be caused solely by direct-current conductivity. This is in accord with experiment, the behaviour of the aluminium trisoaps in toluene being similar to that of the bivalent metal oleates. In ionisation processes in the aluminium trisoap solutions, the following equilibria are probably involved :

$$Al(OOC{\cdot}R)_3 \rightleftharpoons Al^+(OOC{\cdot}R)_2 + {}^-OOC{\cdot}R \quad . \quad . \quad . \quad . \quad . \quad (i)$$

$$Al(OOC{\cdot}R)_3 + {}^-OOC{\cdot}R \rightleftharpoons Al^-(OOC{\cdot}R)_4 \quad . \quad . \quad . \quad . \quad . \quad (ii)$$

$$Al(OOC{\cdot}R)_3 + Al^+(OOC{\cdot}R)_2 \rightleftharpoons Al_2{}^+(OOC{\cdot}R)_5 \quad . \quad . \quad . \quad (iii)$$

[12] Jobling, Nelson, and Gilmour, unpublished work.

Aggregation, by the addition of neutral molecules, may proceed beyond stages (ii) and (iii) but the ebullioscopic results and the steric argument make this improbable. As in the case of the bivalent metal oleates in toluene [1] the stability of these ions in a solvent of such low dielectric constant as toluene is explained by the shielding effect of the hydrocarbon chains which prevents close approach of the ionic charges localised in the centre of the aggregates.

The dielectric loss data for aluminium trilaurate (Fig. 7) suggest that these ionisation processes are important even in the solid and might largely determine the dielectric properties of the trisoap above its melting point. No dielectric measurements, however, have so far been made on the liquid soaps.

THE QUEEN'S UNIVERSITY OF BELFAST. [*Received, March 28th*, 1956.]

---

671. *Structural Chemistry of the Alkoxides. Part VII.*[1] *Secondary Alkoxides of Quadrivalent Cerium and Thorium.*

By D. C. BRADLEY, A. K. CHATTERJEE, and W. WARDLAW.

Ceric secondary alkoxides, $Ce(O{\cdot}CHR_2)_4$ where R = Me or Et, and $Ce(O{\cdot}CHMeR)_4$ where R = Et, Pr^n, or Pr^i, have been prepared and their molecular weights determined ebullioscopically in benzene and in toluene. Ceric tetra*iso*propoxide sublimed at 160—170°/0·05 mm. but the other derivatives were non-volatile. The non-volatile thorium secondary alkoxides $Th(O{\cdot}CHEtR)_4$, where R = Me or Et, have also been prepared and their molecular weights determined ebullioscopically in benzene. The molecular weights and volatilities of the secondary alkoxides of Ti, Zr, Ce(IV), and Th are discussed from the theoretical viewpoint.

IN Part VI [1] we reported that the molecular complexities of thorium *n*-alkoxides were considerably greater than the complexities of the corresponding alkoxides of quadrivalent cerium, and suggested that (i) the pronounced ionic character of thorium alkoxides enhanced the polymerisation, or (ii), on a stereochemical basis, the atomic radius of thorium was greater than that of cerium although the literature suggests that their radii are equal. Moreover, it was clear from the anomalous behaviour of the *neo*pentyloxides of cerium and thorium that stereochemical factors were operative. Consequently it seemed worthwhile to investigate fully the effect of chain branching on the properties of cerium alkoxides. In this communication we report the results obtained on some secondary alkoxides of cerium and thorium. The following derivatives were prepared: $Ce(O{\cdot}CHR_2)_4$, where R = Me and Et; $Ce(O{\cdot}CHMeR)_4$, where R = Et, Pr^n, or Pr^i; and $Th(O{\cdot}CHEtR)_4$, where R = Me or Et.

Alcohol interchange from the *iso*propoxides was employed for the preparations. In addition, the cerium derivatives of pentan-3-ol and 3-methylbutan-2-ol were obtained from dipyridinium cerium hexachloride by the ammonia method:

$$(C_5H_5N)_2CeCl_6 + 4ROH + 6NH_3 \longrightarrow Ce(OR)_4 + 6NH_4Cl + 2C_5H_5N$$

The crystalline *iso*propoxide, $Ce(OPr^i)_4.Pr^iOH$, also obtained from the pyridinium salt,[1] dissociated at 100°/0·05 mm. and gave the tetra*iso*propoxide as a yellow glass, readily soluble in organic solvents. The tetra*iso*propoxide volatilised in a "molecular still" at 160—170°/0·05 mm. and gave a yellow-green crystalline sublimate which slowly reverted to the original yellow colour when allowed to cool under nitrogen. None of the other secondary alkoxides of cerium could be sublimed under reduced pressure. The molecular weights of all the new cerium alkoxides were determined ebullioscopically in benzene and in toluene (see Table 1).

It is remarkable that there appears to be no systematic variation of molecular complexity with size or configuration of the secondary alkyl group in these compounds either in benzene or toluene. However, the average value in toluene (2·80 ± 0·02) is significantly lower than the average value in benzene (3·04 ± 0·11) and this is consistent

[1] Part VI, *J.*, 1956, 2260.

with the predicted decrease in molecular complexity with increase in boiling point of the solvent, owing to thermal dissociation.[3] This effect is much smaller in the secondary alkoxides than in the primary alkoxides of cerium (complexities: 4·22 in benzene and

TABLE 1.

R in $Ce(OR)_4$	Benzene		Toluene	
	M	Complexity	*M*	Complexity
Me_2CH	1179	3·13	1045	2·78
MeEtCH	1293	2·99	1210	2·80
MePr^{n}CH	1520	3·11	1363	2·79
MePr^{i}CH	1464	3·00	1377	2·82
Et_2CH	1420	2·90	1370	2·80

3·43 in toluene). We have already drawn attention to the striking behaviour of the *neo*pentyloxide group in the metal alkoxides and it is especially noteworthy that although cerium *neo*pentyloxide is less volatile than cerium *iso*propoxide yet it has the lower molecular complexity both in benzene and in toluene. Another interesting feature of Table 1 is that the complexities of the secondary alkoxides of cerium are significantly lower in both solvents than the complexities of the primary alkoxides. It is therefore evident that branching of the alkyl group leads to a decrease in molecular complexity in conformity with our stereochemical theory for the metal alkoxides. By the arguments advanced previously [1] it appears that in the secondary alkoxides of quadrivalent cerium the central atom is predominantly exhibiting the co-ordination number of six compared with the approximately equal degrees of 6- and 8-co-ordination suggested for the normal alkoxides. Moreover, the behaviour of the normal and secondary alkoxides in benzene and in toluene suggests that the intermolecular bonding in the 6-co-ordinate complexes is stronger than in the 8-co-ordinate complexes. Thus according to our structural models the proportions of 8-co-ordinate and 6-co-ordinate cerium are 46% and 54% respectively in boiling benzene, and 20% and 80% respectively in boiling toluene for the normal alkoxides. For the secondary alkoxides the cerium is predominantly 6-co-ordinate (~98%) in boiling benzene with only a small percentage in the 8-co-ordinate state, whilst in boiling toluene it appears that further dissociation of the trimeric molecules to the monomeric 4-co-ordinate state has only reduced the 6-co-ordinate cerium to 96% of the total. Although these calculations involve a gross simplification they undoubtedly illustrate the much greater dissociation of the 8-co-ordinate complexes compared with the 6-co-ordinate complexes over the same temperature range.

The preparation of some new alkoxides of thorium allows us to compare the molecular complexities (in boiling benzene) of a number of secondary alkoxides of titanium, zirconium, cerium, and thorium. Table 2 shows that the complexities of thorium secondary

TABLE 2.

R in $M(OR)_4$	M = Ti †	Zr †	Ce *	Th
Me_2CH	1·4	3·0	3·1	3·8 ‡
MeEtCH	—	2·5	3·0	4·2 *
MePr^{n}CH	1·0	2·0	3·1	—
MePr^{i}CH	1·0	2·0	3·0	—
Et_2CH	1·0	2·0	2·9	4·1 *

* This research. † Ref. 3. ‡ Ref. 4.

alkoxides are considerably greater than those of the corresponding cerium derivatives, which in turn are greater than those of zirconium secondary alkoxides. It is especially noteworthy that, although the complexities of cerium and thorium secondary alkoxides are lower than those of the normal alkoxides owing to the shielding effect of the branched alkoxide groups, yet the complexities of these secondary alkoxides do not depend on the size of the alkyl group. On the other hand, the corresponding zirconium secondary alkoxides show a marked dependence of complexity on the size of the alkyl group. This contrast in behaviour is probably due to the smaller shielding requirements of zirconium compared

[1] Bradley, Wardlaw, and Whitley, *J.*, 1956, 5.
[3] Bradley, Mehrotra, and Wardlaw, *J.*, 1952, 5020.
[4] Bradley, Saad, and Wardlaw, *J.*, 1954, 1091.

with cerium and thorium and this is in line with the fact that for titanium, which has a smaller atomic radius than zirconium, all of the secondary alkoxides except the *iso*propoxide are monomeric. The differences in molecular complexities of the Group IVA secondary alkoxides are also reflected in the volatilities of these compounds. Thus all of the titanium and zirconium secondary alkoxides may be distilled under reduced pressure, the titanium compounds being the more volatile. However, with cerium and thorium only the *iso*propoxides could be volatilised and it is significant that cerium *iso*propoxide, which has the same molecular complexity as zirconium *iso*propoxide, can be sublimed in the molecular still at a temperature near to the boiling point (at 0·1 mm.) of the zirconium derivative. The lack of volatility of the higher secondary alkoxides of cerium is evidently due to the increase in latent heat of sublimation which results from the increase in size of the trimeric molecules from the *iso*propoxide to the derivative of pentan-3-ol. This view is supported by the behaviour of the corresponding zirconium compounds. For example, the complexities of the compounds $Zr(O{\cdot}CHMe_2)_4$, $Zr(O{\cdot}CHMeEt)_4$, and $Zr(O{\cdot}CHEt_2)_4$ are 3·0, 2·5, and 2·0 respectively, while the boiling points (at 0·1 mm.) are 160°, 164°, and 181° respectively. This shows that the tendency towards increased volatility caused by the lowering of the molecular complexity is not quite sufficient to counterbalance the opposing effect due to increase in the size of the alkyl groups. In the case of cerium or thorium secondary alkoxides the effect of increased size of the alkyl groups is unopposed since there is no change in molecular complexity.

It is clear from the data in Table 2 that the order of molecular complexities of these compounds is always Th > Ce > Zr > Ti. If stereochemical factors are primarily responsible for this behaviour then it follows that the order of atomic radii should be Th > Ce > Zr > Ti and this agrees with our conclusion from the study of the normal alkoxides.[1] However, we have also pointed out that the ionic character of thorium alkoxides may be another factor to consider in this comparison because electrostatic attraction involving $\overset{\delta+}{Th}\text{–}\overset{\delta-}{OR}$ dipoles might cause enhanced molecular association. Alternatively it is possible that intermolecular bonding of the type $\begin{matrix} M \\ R \end{matrix}\!\!>\!O \longrightarrow M$ is stronger in thorium alkoxides than in the cerium alkoxides and this point will be further considered when dealing with the tertiary alkoxides. The molecular weight of cerium *iso*propoxide was also determined in boiling *iso*propyl alcohol and showed that the compound was dimeric and thus resembled zirconium *iso*propoxide.[5] The *iso*propoxides of zirconium and cerium give derivatives of the type $M(OPr^i)_4.Pr^iOH$ and $M(OPr^i)_4.C_5H_5N$, and it seems reasonable to suppose that in these compounds the metals are 6-co-ordinated, as depicted in the dimeric structure proposed earlier for the zirconium compound.[5] On the other hand, thorium *iso*propoxide, which does not form complexes of the above type, gave a molecular complexity of 1·8 in boiling *iso*propyl alcohol[4] and this low result may well be due to ionic dissociation, as indicated by the alkaline reaction of the solution.

Experimental

The experimental details were similar to those previously described.[1]

Preparation of Alkoxides of Cerium and Thorium.—Typical results are presented in Table 3.

Table 3.

R	ROH taken (c.c.)	Starting material (g.)	C_5H_5N (c.c.)	New alkoxide (g.)	Metal (%) Found	Calc.
MeEtCH	40	4·14 [a]	200	4·0	32·4 [d]	32·4
,, ...	20·5	4·32	80	4·84	44·3 [e]	44·3
$MePr^nCH$	15·4	5·26 [a]	100	5·73	28·6 [d]	28·7
$MePr^iCH$	38·5	21·2 [b]	150	5·8	28·8 [d]	28·7
,, ...	14·8	6·47 [a]	110	2·6 [a] + 4·2 †	28·7 [d]	28·7
Et_2CH	21·0	7·68 [a]	200	8·49	28·8 [d]	28·7
,, ...	10·9	4·57 [c]	75	5·01	40·3 [e]	40·0
,, ...	35	19·5 [b]	150	9·85	28·8 [d]	28·7

[a] $Ce(OPr^i)_4.Pr^iOH$; [b] $(C_5H_5N)_2CeCl_6$; [c] $Th(OPr^i)_4$; [d] Ce; [e] Th.
* 1st crop. † 2nd crop.

[4] Bradley, Mehrotra, Swanwick, and Wardlaw, *J.*, 1953, 2025.

Molecular-weight Determinations.—Determinations by the method involving the use of the apparatus constant (found with azobenzene) were checked by "internal calibration" with fluorene.[1] The results obtained by the two methods differed by less than 1%. Typical results

TABLE 4.

Alkoxide	Range in *m* (g.)	Wt. of benzene (g.)	$\Delta T/m$ (°c/g.)	Mol. wt. Found	Mol. wt. Calc.
$Ce(OPr^i)_4$	0·0233—0·1985	15·10	0·1645	1180	376·1
$Ce(OPr^i)_4.Pr^iOH$	0·0171—0·2652	12·50 *	0·1415	850	436·1
$Ce(O{\cdot}CHMeEt)_4$	0·0322—0·2568	15·30	0·1480	1295	432·1
$Ce(O{\cdot}CHEt_2)_4$	0·0593—0·3002	15·76	0·1310	1420	488·1
$Ce(O{\cdot}CHMePr^n)_4$	0·0217—0·2600	14·63	0·1320	1520	488·1
$Ce(O{\cdot}CHMePr^i)_4$	0·0449—0·1936	16·01	0·1185	1465	488·1
$Th(O{\cdot}CHMeEt)_4$	0·0582—0·2502	14·48	0·0920	2200	524·1
$Th(O{\cdot}CHEt_2)_4$	0·0479—0·2259	14·48	0·0875	2330	580·1

* In boiling *iso*propyl alcohol.

TABLE 5.

R in $Ce(OR)_4$	Alkoxide: Range in *m* (g.)	Alkoxide: $\Delta T/m$ (mm./g.) *	Fluorene: Range in *m* (g.)	Fluorene: $\Delta T/m$ (mm./g.) *	Mol. wt. Found	Mol. wt. Calc.
Me_2CH	0·0370—0·1750	112	0·0062—0·0213	712	1055	376·1
MeEtCH	0·0310—0·1692	100	0·0048—0·0365	728	1210	432·1
Et_2CH	0·0554—0·2380	100	0·0038—0·0255	825	1370	488·1
$MePr^nCH$	0·0136—0·1062	75	0·0062—0·0432	615·5	1365	488·1
$MePr^iCH$	0·0332—0·1400	64·5	0·0130—0·0318	534	1375	488·1

* ΔT in mm. of water pressure.

for the first method (in benzene or *iso*propyl alcohol) are given in Table 4 and for the internal calibration method (in toluene) in Table 5.

The authors are indebted to Imperial Chemical Industries Limited for a Grant for purchasing the ceric ammonium sulphate, and one of them (A. K. C.) thanks Patna University for study leave.

BIRKBECK COLLEGE, MALET ST., LONDON, W.C.1. [*Received, April 10th*, 1956.]

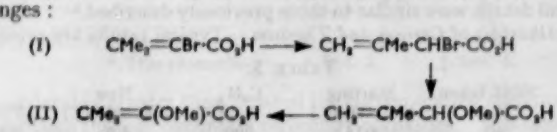
---

672. *The Reactivity of 2-Bromopent-2-enoic Acid.*

By B. J. P. ALLES and M. U. S. SULTANBAWA.

2-Bromopent-2-enoic acid with methanolic sodium methoxide gives 2-methoxypent-3-enoic acid and smaller amounts of the 2-enoic isomer. The latter is formed from the former.

OWEN and one of us [1] showed that α-bromo-ββ-dimethylacrylic acid (I) with methanolic sodium methoxide gave α-methoxy-ββ-dimethylacrylic acid (II) by reactions involving prototropic changes :

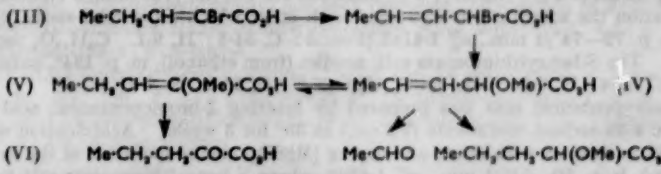


and it has been suggested that α-bromocrotonic acid yields α-methoxycrotonic acid by a similar mechanism. The differences shown by these two bromo-acids cannot be related to the position of equilibrium of the unsubstituted acids as crotonic and ββ-dimethylacrylic acid both exist almost wholly in the αβ-form.[2,3] Newman and Owen [4] studied α-bromo-*cyclo*hexylideneacetic acid because at equilibrium *cyclo*hexylideneacetic acid affords *ca.* 88%

[1] Owen and Sultanbawa, *J.*, 1949, 3089.
[2] Kon and Linstead, *J.*, 1925, **127**, 616.
[3] Linstead and Noble, *J.*, 1934, 614.
[4] Newman and Owen, *J.*, 1952, 4713.

of the βγ-isomer: this bromo-acid gave α-*cyclo*hex-1-enyl-α-methoxyacetic acid which could not be isomerised to αβ-unsaturated α-*cyclo*hexylidene-α-methoxyacetic acid.

Concurrently [5] with the last-mentioned investigation we studied 2-bromopent-2-enoic acid (pent-2-enoic acid at equilibrium affords 32% of the -3-enoic isomer [3]). Liberation of bromide ion from this bromo-acid (III) was complete in 6 hr. in presence of methanolic sodium methoxide at 100° or in 9 hours at 70°, but the yield was better at the lower temperature. The product was shown to be a mixture of 2-methoxypent-3- (IV) and -2-enoic acid (V), as follows. The general nature of the mixture was shown by hydrogen-



ation to 2-methoxypentanoic acid, an authentic sample of which, obtained from 2-bromopentanoic acid by means of sodium methoxide at room temperature, gave an identical *S*-benzylthiuronium salt (although analysis of this salt was unsatisfactory). The presence of 2-methoxypent-2-enoic acid (V) in the mixture was shown by formation of methanol on acid hydrolysis and by formation of the *p*-nitro- and 2 : 4-dinitro-phenylhydrazone of 2-oxopentanoic acid when the mixture was treated with an acid solution of the hydrazine. Ozonolysis of the mixture gave acetaldehyde in amount indicating that 2-methoxypent-3-enoic acid was the main constituent.

The reaction mechanism was established by the methods used earlier.[1] Treatment of the distilled reaction product with 2 : 4-dinitrophenylhydrazine showed it to contain *ca.* 10% of 2-methoxypent-2-enoic acid (V). Heating the product with 5N-sodium hydroxide increased this proportion to 35%, but this fell to 20% when the alkali-treated mixture was distilled. This change during distillation was confirmed by a change in the ultraviolet absorption maximum from ε 5550 at 220 mμ to ε 2290 at 210 mμ, and may have been due to decarboxylation [6] (this may also have accounted for Newman and Owen's failure [4] to isolate α-*cyclo*hexylidene-α-methoxyacetic acid).

Experimental

M. p.s were determined on a hot stage.

Pent-2-enoic acid (prepared [7] from propaldehyde and malonic acid in pyridine containing a trace of piperidine), b. p. 71—73°/1·5 mm., with bromine in carbon disulphide at −10° in sunlight or ultraviolet light gave a crude dibromide whence Bachmann's method [8] afforded 2-bromopent-2-enoic acid, needles [from light petroleum (b. p. 40—60°)], m. p. 49—50°, ultraviolet absorption max. at 228 mμ (ε 6500) in EtOH.

Reaction of 2-Bromopent-2-enoic Acid with Methanolic Sodium Methoxide.—(*a*) The bromo-acid (0·9 g.) and methanolic sodium methoxide (3 equivs.) were heated at 70° or 100° for the times stated below. The methanol was then removed under slightly diminished pressure, the residue acidified (Congo-red) with 5N-sulphuric acid and extracted with ether, the aqueous layer neutralised with calcium carbonate, and bromide ion determined by titration with silver nitrate (chromate indicator). Results are tabulated.

	100°						70°	
Concn. (N) of NaOMe.....	1·0	1·0	1·8	2·7	2·7	5·5	2·7	2·7
Time (hr.)	2	6	2	3	6	3	6	9
Reaction (%)	70	98	70	97	100	98	90	94

(*b*) The bromo-acid (18·0 g.) was heated with methanolic 1·35N-sodium methoxide (136 c.c.) at 70—75° for 9 hr. with occasional shaking. After evaporation in a vacuum, the residue was

[5] Cf. Alles and Sultanbawa, *Proc. Ceylon Assoc. Adv. Sci.*, 1950, **6**, II, 27.
[6] Cf. Arnold, Elmer, and Dodson, *J. Amer. Chem. Soc.*, 1950, **72**, 4359.
[7] Goldberg and Linstead, *J.*, 1928, 2343.
[8] Bachmann, *J. Amer. Chem. Soc.*, 1933, **55**, 4279.

dissolved in ice-cold 5N-sulphuric acid and extracted with ether. The dried ($MgSO_4$) extracts, on evaporation, gave an oil (8·5 g., 66%) which by fractionation afforded a mixture (A) (5·7 g., 44%), b. p. 69—70°/0·5 mm., n_D^{20} 1·4474, u.v. absorption max. at 210 mμ (ε 2280), of 2-methoxypent-2- and -3-enoic acid, which gave faulty analyses (Found: C, 56·3, 56·1; H, 7·25, 7·8%; equiv., 130·3. Calc. for $C_6H_{10}O_3$: C, 55·4; H, 7·75%; equiv., 130·1). The mixture afforded a *S-benzylthiuronium salt*, needles (from ethanol), m. p. 151—152° (Found: C, 56·9; H, 6·6; N, 9·3. $C_{14}H_{20}O_3N_2S$ requires C, 56·7; H, 6·8; N, 9·45%).

Hydrogenation of the Mixture (A).—In water (40 c.c.) containing sodium carbonate (1·2 g.) and Raney nickel (0·5 g.), the oil (1·3 g.) absorbed 230 c.c. (30°/760 mm., 0·93 mol.) of hydrogen. After filtration the solution was extracted with ether which removed *2-methoxypentanoic acid* (0·6 g.), b. p. 72—74°/1 mm., n_D^{20} 1·4185 (Found: C, 54·5; H, 9·1. $C_6H_{12}O_3$ requires C, 54·5; H, 9·2%). The *S*-benzylthiuronium salt, needles (from ethanol), m. p. 134°, gave poor analyses (Found: C, 57·4; H, 7·5. Calc. for $C_{14}H_{22}O_3N_2S$: C, 56·3; H, 7·4%).

2-Methoxypentanoic acid was prepared by treating 2-bromopentanoic acid (1·8 g.) with methanolic 4·5N-sodium methoxide (7·5 c.c.) at 30° for 3 weeks. Acidification with 5N-hydrochloric acid, extraction with ether, and drying ($MgSO_4$) and evaporation of the extract gave the acid (1·4 g.), b. p. 70—74°/1 mm., n_D^{20} 1·4205, whose *S*-benzylthiuronium salt formed needles, m. p. 134° alone or mixed with the salt described in the preceding paragraph.

Hydrolysis of the Mixture (A).—(*a*) Hydrolysis of the mixture with 5N-sulphuric acid and subsequent distillation gave a distillate affording a positive resorcinol test for methanol.

(*b*) When the mixture (A) was kept with *p*-nitrophenylhydrazine in 5N-hydrochloric acid overnight, a yellow solid separated which on crystallisation from ethanol had m. p. 186° alone or mixed with the *p*-nitrophenylhydrazone, m. p. 186—187° (Found: N, 16·3. Calc. for $C_{11}H_{13}O_4N_3$: N, 16·7%), of 2-oxopentanoic acid which had been prepared from ethyl 3-ethoxycarbonylpentanoate by Adickes and Andresen's method.[9] The authentic ester had b. p. 86—87°/0·7 mm. and gave a 2 : 4-dinitrophenylhydrazone, m. p. 99°; the authentic acid gave a 2 : 4-dinitrophenylhydrazone, m. p. 167°.

(*c*) With a 1% solution of 2 : 4-dinitrophenylhydrazine the mixture A gave a 2 : 4-dinitrophenylhydrazone, m. p. 166—167° (from ethanol) alone or mixed with that described in (*b*).

Ozonolysis of Mixture A.—The mixture (0·5 g.) was ozonised in carbon tetrachloride (15 c.c.) at −10° for 3 hr. After evaporation the residue was distilled in steam. The distillate afforded the dimedone derivative, m. p. and mixed m. p. 141°, and 2 : 4-dinitrophenylhydrazone, m. p. and mixed m. p. 146—147°, of acetaldehyde. The non-volatile residue gave an unidentified bis-2 : 4-dinitrophenylhydrazone.

Experiments bearing on the Reaction Mechanism.—(*a*) The mixture A (100 mg.) with an excess of 2 : 4-dinitrophenylhydrazine in 4N-sulphuric acid gave 2-(2 : 4-dinitrophenylhydrazono)pentanoic acid (20 mg.), corresponding to *ca.* 10% of 2-methoxypentanoic acid.

(*b*) The mixture A (2·0 g.) was heated with 5N-sodium hydroxide (10 c.c.) for 20 hr. at 100°. The mixture was cooled, acidified (Congo-red) with cold 5N-hydrochloric acid, and extracted with ether. The extract was dried ($MgSO_4$) and evaporated. The residue had b. p. 70—82°/0·5—1 mm., n_D^{20} 1·4500 (0·75 g.). Part (100 mg.) of the distillate gave, as above, 2-(2 : 4-dinitrophenylhydrazono)pentanoic acid (50 mg., *ca.* 20%).

(*c*) Experiment (*b*) was repeated except that the product was not distilled. The product, $\lambda_{max.}$ 220 mμ (ε 5550), gave 90 mg. (*ca.* 35%) of the above-mentioned phenylhydrazone.

(*d*) 2-Bromopent-2-enoic acid (0·45 g.) was heated with methanolic 2·25N-sodium methoxide (3·4 c.c.) for 7 hr. at 70—75°. The solution was cooled, acidified with dilute sulphuric acid, and treated with 2 : 4-dinitrophenylhydrazine in 4N-sulphuric acid (100 c.c.). After 6 weeks at *ca.* 30° 0·246 g. (*ca.* 33%) of the above-mentioned 2 : 4-dinitrophenylhydrazone was collected.

(*e*) Experimentation as in (*d*), but with 32 hours' heating, gave 0·657 g. (*ca.* 88%) of hydrazone.

We thank Dr. L. N. Owen for his advice and interest, and (the late) Professor A. Kandiah, Professor E. L. Fonseka, and Dr. S. L. de Silva for facilities.

Department of Chemistry, Ceylon Technical College, Colombo, 11.
Department of Chemistry, University of Ceylon, Colombo, 3.

[*Received, February 20th*, 1956.]

[9] Adickes and Andresen, *Annalen*, 1944, **555**, 55.

673. *Anomalies in the Reduction of 2 : 2′-Diacetyldiphenyl.*

By D. Muriel Hall, Joan E. Ladbury, Mary S. Lesslie, and E. E. Turner.

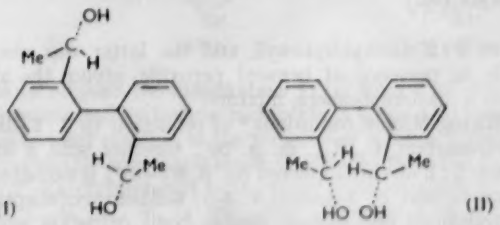
2 : 2′-Diacetyldiphenyl gives 9 : 10-dimethylphenanthrene on Clemmensen reduction. With lithium aluminium hydride it gives two diastereoisomeric 2 : 2′-di-(1-hydroxyethyl)diphenyls. These react normally with hydrobromic acid and, by the action of boiling quinoline on the resulting mixture of isomerides, 2 : 2′-divinyldiphenyl has been prepared. Reduction of 2 : 2′-diacetyldiphenyl under Huang-Minlon conditions gives 2-methyl-3 : 4-5 : 6-dibenzo*cyclo*hepta-1 : 3 : 5-triene.

2 : 2′-Di-(1-hydroxy-1-methylethyl)diphenyl can be dehydrated in three ways, to give (*a*) 2 : 7 : 7-trimethyl-3 : 4-5 : 6-dibenzo*cyclo*hepta-1 : 3 : 5-triene, (*b*) 2 : 2′-di*iso*propenyldiphenyl, or (*c*) 2 : 7-dihydro-2 : 2 : 7 : 7-tetramethyl-3 : 4-5 : 6-dibenzoxepin.

A possible route to 2 : 2′-diethyldiphenyl (see Everitt, Hall, and Turner [1]) appeared to be the Clemmensen reduction of 2 : 2′-diacetyldiphenyl. Since the latter is produced by the oxidation of 9 : 10-dihydro-9 : 10-dihydroxy-9 : 10-dimethylphenanthrene, obtained by the action of a Grignard reagent on phenanthraquinone, the method might be applicable to the preparation of a series of 2 : 2′-dialkyldiphenyls.

However, the Clemmensen reduction of 2 : 2′-diacetyldiphenyl gave a high yield of 9 : 10-dimethylphenanthrene. Other sterically hindered ketones have been observed to give anomalous products on Clemmensen reduction (cf. Brewster, Patterson, and Fidler [2]) and acetophenone itself gives predominantly styrene instead of ethylbenzene under certain conditions.[3]

Other methods of reduction were then investigated. With lithium aluminium hydride reduction proceeded normally to give a mixture of two isomeric 2 : 2′-di-(1-hydroxyethyl)-diphenyls. By tedious fractional crystallisation it was possible to isolate the individual diols, *A*, m. p. 147·5—149°, and *B*, m. p. 153—155°. These are presumably the two diastereoisomeric (racemic and *meso*) forms resulting from the presence of two asymmetric carbon atoms. There was no evidence of further stereoisomerism arising from restricted rotation of the diphenyl skeleton, and the evidence of optical instability in related compounds [*e.g.*, 2′-(1-hydroxy-1-methylethyl)diphenyl-2-carboxylic acid [4]] suggests that such stereoisomerism would be of an unstable type. The *meso*-compound is of particular interest in that it can pass through a conformation in which it has a centre of symmetry (I), but not through one in which it has a plane of symmetry (II), since it would be im-

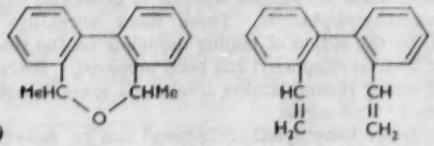


possible for the two substituent groups to be accommodated on the same side of the diphenyl skeleton whilst the benzene nuclei in the latter were coplanar. Unfortunately the quantities of pure diols were insufficient for investigation of them by optical resolution.

The diols were dehydrated separately by heating them with 20% sulphuric acid and gave 2 : 7-dihydro-2 : 7-dimethyl-3 : 4-5 : 6-dibenzoxepin (III). This also appeared to be

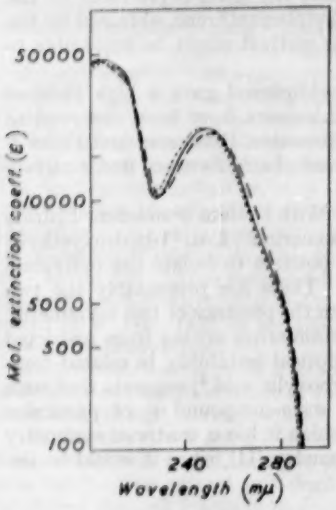
[1] Everitt, Hall, and Turner, *J.*, 1956, 2286.
[2] Brewster, Patterson, and Fidler, *J. Amer. Chem. Soc.*, 1954, **76**, 6368.
[3] Clemmensen, *Ber.*, 1913, **46**, 1837.
[4] Corbellini and Angeletti, *Atti R. Accad. Lincei*, 1932, **15**, 968; Jamison and Turner, *J.*, 1942, 437.

a mixture of diastereoisomers but only one form was isolated and was probably not stereochemically pure. This form was the main product from diol *A*. Diol *B* reacted much more slowly and the product was more obviously a mixture, but after several crystallisations the melting point of the oxepin approached that of the oxepin from *A* and was not depressed in the presence of the latter.



(III) (IV)

The two diols reacted with hot hydrobromic acid to give what was evidently a mixture of diastereoisomeric dibromo-compounds. When heated with quinoline these mixtures gave 2 : 2′-divinyldiphenyl (IV), a crystalline specimen of which, unlike 4 : 4′-divinyldiphenyl,[5] showed no sign of polymerisation. Catalytic hydrogenation of the divinyl



———— 1-*Hydroxymethyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-3 : 5-*diene*.
– – – – 2-*Methyl*-3 : 4-5 : 6-*dibenzocyclohepta*-3 : 5-*diene* (VI).
— — — 2 : 7 : 7-*Trimethyl*-3 : 4-5 : 6-*dibenzocyclohepta*-3 : 5-*diene* (XIV).

derivative (IV) gave 2 : 2′-diethyldiphenyl, and the latter was readily brominated by *N*-bromosuccinimide in presence of benzoyl peroxide, giving the above two dibromo-compounds, again as a diastereoisomeric mixture.

Application of Huang-Minlon conditions [6] of reduction to 2 : 2′-diacetyldiphenyl gave an unsaturated hydrocarbon, $C_{16}H_{14}$, m. p. 50°, together with a little 9 : 10-dimethylphenanthrene. Since 2 : 2′-divinyldiphenyl (m. p. 80—81°) is excluded, the only apparent alternative structure is that of 2-methyl-3 : 4-5 : 6-dibenz*ocyclo*hepta-1 : 3 : 5-triene (V). The hydrocarbon contained one olefinic double bond (titration with bromine) and on catalytic hydrogenation gave a non-olefinic hydrocarbon, $C_{16}H_{16}$, with an ultraviolet absorption spectrum very similar to that of 1-hydroxymethyl-3 : 4-5 : 6-dibenz*ocyclo*hepta-3 : 5-diene [7] (see Table and Figure). The non-olefinic hydrocarbon must therefore be 2-methyl-3 : 4-5 : 6-dibenz*ocyclo*hepta-3 : 5-diene (VI). Further proof of the structure of the triene (V) comes from its behaviour on oxidation. With selenium dioxide it gave a monoketone (VII), isolated as the 2 : 4-dinitrophenylhydrazone. On oxidation with

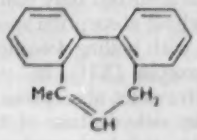
[5] Valyi, Janssen, and Mark, *J. Phys. Chem.*, 1945, **49**, 461.
[6] Huang-Minlon, *J. Amer. Chem. Soc.*, 1946, **68**, 2487.
[7] Beaven, Bird, Hall, Johnson, Ladbury, Lesslie, and Turner, *J.*, 1955, 2708.

Ultraviolet absorption spectra.

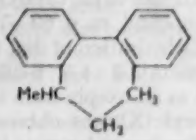
	Short-wave band				Conjugation band		Long-wave features	
	$\lambda_{max.}$	ε	$\lambda_{min.}$	ε	$\lambda_{max.}$	ε	$\lambda_{inf.}$	ε
1-Hydroxymethyl-3 : 4-5 : 6-dibenzo-*cyclo*hepta-3 : 5-diene [7]	206	45,500	227·5	5150	248·5	15,200	(*ca.* 277)	*ca.* 1450
2-Methyl-3 : 4-5 : 6-dibenzo*cyclo*-hepta-3 : 5-diene (VI)	205·5	44,000	227	5830	248	15,300	(*ca.* 276)	*ca.* 1400
2 : 7 : 7-Trimethyl-3 : 4-5 : 6-dibenzo-*cyclo*hepta-3 : 5-diene (XIV)	205	45,000	229	5350	250	14,200	(*ca.* 278)	*ca.* 1500

Solvent, light petroleum (b. p. 80—100°); wavelengths in mμ; values in parentheses denote inflections.

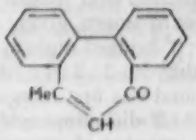
sodium dichromate in acetic acid it gave phenanthraquinone, 2-acetyldiphenyl-2′-carboxylic acid, and 2-acetyl-2′-formyldiphenyl. The behaviour closely resembles that of 3 : 4-5 : 6-dibenzo*cyclo*hepta-1 : 3 : 5-triene [8] and of deaminocolchinol methyl ether [9] on similar oxid-



(V)



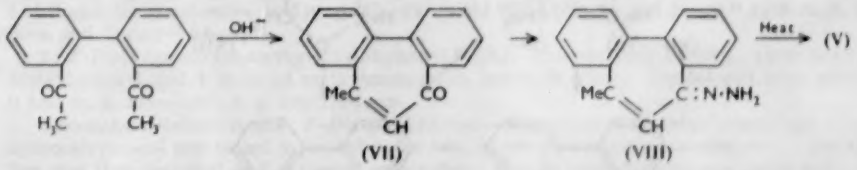
(VI)



(VII)

ation. Oxidation with sodium dichromate in acetic acid to phenanthraquinone is used by Cook, Loudon, *et al.*[8,9,10,11] as a test for the bridged diphenyl system. However, as a check on the validity of this test, we subjected 2 : 2′-divinyldiphenyl to oxidation under similar conditions and, rather surprisingly, found that this compound, too, gave phenanthraquinone.

A possible route from diacetyldiphenyl to the cyclic triene (V) is an aldol-type condensation (in the presence of the sodium hydroxide) to give the monoketone (VII), followed by hydrazone formation and normal decomposition :



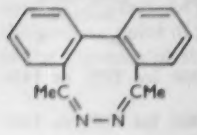
(VII) (VIII)

Attempts were made to prepare the monoketone (VII) from 2 : 2′-diacetyldiphenyl; the latter was practically unaffected by hydrogen chloride in acetic acid solution or by " piperidine–acetate." It underwent reaction in the presence of sodium hydroxide under various conditions but no recognisable compound could be isolated from the product.

Treatment of 2 : 2′-diacetyldiphenyl with warm aqueous-alcoholic hydrazine gave a colourless compound, $C_{16}H_{14}N_2$, m. p. 167—168°, together with some 9 : 10-dimethylphenanthrene. Separation was effected by extracting the unknown compound with warm dilute hydrochloric acid and reprecipitating it with ammonia. On hydrolysis with boiling dilute sulphuric acid the unknown compound gave 2 : 2′-diacetyldiphenyl and when heated with sodium hydroxide in triethylene glycol it gave only 9 : 10-dimethylphenanthrene. It must therefore be 3 : 8-dimethyl-4 : 5-6 : 7-dibenzo-1 : 2-diazocine (IX). The alternative formula (VIII) is precluded by the result of acid hydrolysis, by the failure of the

[8] J. W. Cook, Dickson, and Loudon, *J.*, 1947, 746.
[9] Barton, J. W. Cook, and Loudon, *J.*, 1945, 176.
[10] J. W. Cook, Jack, Loudon, Buchanan, and MacMillan, *J.*, 1951, 1397.
[11] J. W. Cook, Loudon, and Razdan, *J.*, 1954, 4234.

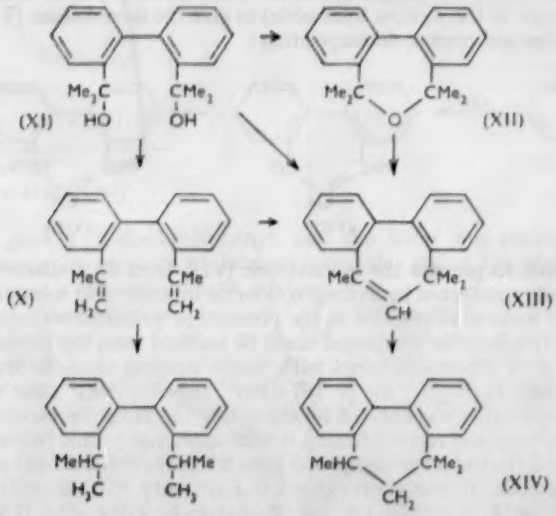
compound to give a salicylidene derivative, and by its failure to decolorise bromine water. The formation of the eight-membered ring azine (IX) and its subsequent decomposition presumably accounts for the 9 : 10-dimethylphenanthrene isolated from the products of the Huang-Minlon reduction. However, the formation of 9 : 10-dimethylphenanthrene during the preparation of the cyclic azine (IX) is less easily accounted for, since the azine itself is stable under the conditions used. It was unaffected by hot aqueous-alcoholic hydrazine or sodium hydroxide or when heated above its melting point, alone or with copper bronze.



(IX)

Meerwein–Ponndorf–Verley reduction of 2 : 2′-diacetyldiphenyl was also attempted but the product appeared to be a mixture and no pure compounds could be isolated.

2 : 2′-Di*iso*propenyldiphenyl (X) was required for comparison of its absorption spectrum with that of 2 : 2′-divinyldiphenyl. Accordingly 2 : 2′-di-(1-hydroxy-1-methylethyl)diphenyl (XI) was prepared,[12] and dehydrated at 140° with naphthalene-2-sulphonic acid, giving a hydrocarbon, $C_{18}H_{18}$, m. p. 100—101° (Cook and Turner [12] give m. p. 97—98°). On hydrogenation over Adams's platinum oxide catalyst this absorbed only one molecular proportion of hydrogen, giving a compound, m. p. 69—71°, whose absorption spectrum was that of a 2 : 2′-bridged diphenyl. Dehydration of diol (XI) with boiling 4N-sulphuric acid gave 2 : 7-dihydro-2 : 2 : 7 : 7-tetramethyl-3 : 4-5 : 6-dibenzoxepin (XII), m. p. 92—93°. This compound was first recognised as an oxepin from its ultraviolet absorption spectrum. Authentic 2 : 2′-di*iso*propenyldiphenyl (X) was obtained by dehydration of the boiling diol (XI) in presence of activated alumina and copper bronze; this hydrocarbon absorbed two molecular proportions of hydrogen in the presence of Adams catalyst, giving 2 : 2′-di-*iso*propyldiphenyl,[1] m. p. 67—68°. Cook and Turner's isomeric hydrocarbon must therefore be 2 : 7 : 7-trimethyl-3 : 4-5 : 6-dibenzo*cyclo*hepta-1 : 3 : 5-triene (XIII), and its hydrogenation product 2 : 2 : 7-trimethyl-3 : 4-5 : 6-dibenzo*cyclo*hepta-3 : 5-diene (XIV). The absorption spectrum of the latter is very similar to that of its monomethyl analogue (VI) (see Table and Figure) and quite different from that of a non-bridged diphenyl with two *ortho*-substituents.



The triene (XIII) was also formed by the action of boiling hydrobromic acid on the diol (XI) or the oxepin (XII), or by treatment of the isomeric hydrocarbon (X) with boiling 50% sulphuric or hydrobromic acid. In the absence of acids the diol was remarkably stable and could be distilled unchanged at atmospheric pressure (b. p. 320°).

[12] D. E. Cook and Turner, *J.*, 1937, 117.

In contrast to 2 : 2′-di*iso*propenyldiphenyl (X), 2 : 2′-divinyldiphenyl (IV) reacted normally with hydrobromic acid, undergoing addition to give 2 : 2′-di-(1-bromoethyl)diphenyl, the compound from which it had originally been obtained.

Oxidation of the triene (XIII) with sodium dichromate in acetic acid gave 2-acetyl-2′-formyldiphenyl, a little phenanthraquinone, and unidentified acids.

Experimental

9 : 10-*Dihydro*-9 : 10-*dihydroxy*-9 : 10-*dimethylphenanthrene*.—The following method was a considerable improvement on that of Zincke and Tropp.[13] Finely ground phenanthraquinone (84 g., 1 mol.) was added in approx. 2 g. lots to a Grignard reagent made from magnesium (39 g., 4 atom-equiv.), about 500 c.c. of ether and enough methyl iodide to cause complete dissolution of the magnesium. After addition of 500 c.c. of benzene, the mixture was heated under reflux on a water-bath for 2 hr., the ether being allowed to distil off gradually through a selective condenser. The cooled mixture was added carefully to ice and water, kept well stirred. Dilute sulphuric acid was added until, on continued stirring, no further colour change occurred. The two layers were separated, ether being added to dissolve any solid that separated. The aqueous layer was extracted twice with ether. The combined ethereal extract was washed twice with brine and then several times with concentrated aqueous sodium hydrogen sulphite solution, until the latter, treated with alkali, gave no phenanthraquinone. (The combined bisulphite extracts, on such treatment, gave 6·5 g. of phenanthraquinone, once crystallised from glacial acetic acid.)

The ether–benzene solution was washed with brine and then distilled, without being dried, until the volume was about 300 c.c. On cooling, the diol crystallised and more was obtained from the mother-liquor. Recrystallisation from benzene gave 75 g. of pure diol, m. p. 163—164°. After allowance for the recovered phenanthraquinone, the yield was 88%.

The use of 6 mol. of Grignard reagent did not improve the yield and greatly extended the time of operating.

2 : 2′-*Diacetyldiphenyl*.—Using the calculated amount of chromic anhydride as recommended by Zincke and Tropp [14] the oxidation was incomplete and the product was difficult to purify. The following procedure was found satisfactory :

To a solution of the preceding diol (38 g., 1 mol.) in glacial acetic acid (380 c.c.), at about 70°, was added, during 10 min., chromic anhydride (16 g., 1·5 mol.) in water (160 c.c.). After a further 10 min. at about 70°, excess of water was gradually added, and the crystalline diacetyldiphenyl filtered off and washed with water. The well-pressed solid, crystallised from ethanol and then from *cyclo*hexane, had m. p. 93—94° (yield 89%) (Zincke and Tropp [14] gave m. p. 84°, Cook and Turner [12] 94—95°).

2 : 2′-Di-(1-hydroxy-1-methylethyl)diphenyl [12] (XI) was obtained in 80% yield from diacetyldiphenyl and 4 mols. of methylmagnesium iodide in ether. Crystallised from ethanol, it had m. p. 139—140°, b. p. 320°/760 mm.

Clemmensen Reduction of 2 : 2′-Diacetyldiphenyl.—A mixture of diacetyldiphenyl (28 g.) and hydrochloric acid was boiled under reflux for 6 hr. in presence of amalgamated zinc. The solution was then decanted and extracted with ether. The residue was also repeatedly extracted with boiling ether to dissolve the solid coating the unchanged zinc. Removal of ether from the combined extracts gave a residue (24·5 g.) which, after crystallisation from ethanol, had m. p. 144° (Found : C, 92·8; H, 7·0. Calc. for $C_{16}H_{14}$: C, 93·2; H, 6·8%) and gave a picrate, m. p. 192—193°. 9 : 10-Dimethylphenanthrene [15] has m. p. 144° and its picrate [15] m. p. 192°.

2 : 2′-*Di*-(1-*hydroxyethyl*)*diphenyl*.—Finely ground 2 : 2′-diacetyldiphenyl (11·9 g., 1 mol.) was washed with ether (300 c.c.) into lithium aluminium hydride (2·9 g., 1·5 mols.) in ether (100 c.c.). The mixture was heated for 1 hr. and then decomposed with ethyl acetate, water, and N-sulphuric acid. The solid obtained after removal of the ether was subjected to repeated fractional crystallisations from benzene; the nearly pure diols were finally crystallised from ethanol. *Diol A* was obtained as prisms, m. p. 147·5—149° (Found : C, 79·2; H, 7·6. $C_{16}H_{18}O_2$ requires C, 79·3; H, 7·5%). *Diol B* (which was more soluble than *A* in benzene) was obtained as long prisms, m. p. 153—155° (Found : C, 79·5; H, 7·6%).

2 : 7-*Dihydro*-2 : 7-*dimethyl*-3 : 4-5 : 6-*dibenzoxepin*.—(i) *From diol A*. The diol (1·0 g.) was heated with 20% sulphuric acid (15 c.c.) on a steam-bath for 2½ hr. with occasional shaking.

[13] Zincke and Tropp, *Annalen*, 1908, **362**, 242.
[14] *Idem*, *ibid.*, **363**, 302.
[15] Rimmer, Christiansen, Brown, and Sandin, *J. Amer. Chem. Soc.*, 1950, **72**, 2298.

The oil solidified on cooling. After one crystallisation from ethanol it had m. p. 74—76°, with previous softening. Two further crystallisations from methanol raised the m. p. to 77—80°, with softening from 74° (Found: C, 85·9; H, 7·3. $C_{16}H_{16}O$ requires C, 85·7; H, 7·2%).

(ii) *From diol B.* The diol was treated as above but it was necessary to heat it for 7 hr. to complete the reaction (indicated by the absence of solid in the oil floating on the hot acid). After one crystallisation from methanol the *oxepin* had m. p. 68—73°, with previous softening. Further crystallisation raised the m. p. to 74—78° (mixed m. p. with oxepin from *A*, 75—78°).

2 : 2′-*Di*-(1-*bromoethyl*)*diphenyl*.—The above diol (either *A* or *B* or a mixture of both) was heated for about 15 min. with a large excess of hydrobromic acid (*d* 1·49). The oil solidified on cooling; it was washed with water, dried *in vacuo* over sodium hydroxide, and crystallised several times from light petroleum (b. p. 40—60°) or *n*-hexane. The *dibromide* (*ca.* 20% from either diol) then had m. p. 88—92°, with previous softening (85°) (Found: C, 52·0; H, 4·6; Br, 43·3. $C_{16}H_{16}Br_2$ requires C, 52·2; H, 4·4; Br, 43·4%). Second crops were obtained with lower m. p.s (*e.g.*, 71—79°); these also gave the diene when heated with quinoline and presumably contained more of the second isomer.

2 : 2′-*Divinyldiphenyl* (*with Miss* P. M. Everitt).—A solution of the above dibromide in quinoline was boiled for 5 min. The cooled solution was poured into dilute hydrochloric acid, and the solid separated and crystallised from *n*-hexane and then from methanol. 2 : 2′-*Divinyldiphenyl* had m. p. 80—81° (Found: C, 93·2; H, 6·6. $C_{16}H_{14}$ requires C, 93·2; H, 6·8%). The m. p. was unchanged after several months. Hydrogenation in ethanolic solution at Adams's platinum oxide catalyst gave 2 : 2′-diethyldiphenyl,[1] b. p. 139—140°/13·5 mm., n_D^{25} 1·5626.

Bromination of 2 : 2′-*Diethyldiphenyl* (*with Miss* P. M. Everitt).—2 : 2′-Diethyldiphenyl (21 g., 1 mol.), *N*-bromosuccinimide (35·6 g., 2 mol.), and benzoyl peroxide (0·1 g.) in dry carbon tetrachloride (80 c.c.) were heated under reflux for 3 hr. More carbon tetrachloride (80 c.c.) was added and the hot solution filtered. The solvent was distilled off from the filtrate and the residue was crystallised from light petroleum (b. p. 40—60°), giving 2 : 2′-di-(1-bromoethyl)diphenyl (25·5 g., 70%), m. p. 75—79°, with previous softening. After five crystallisations it had m. p. and mixed m. p. (with a specimen prepared from the diol) 87—90°, with previous softening (Found: C, 52·4; H, 4·6; Br, 44·0. Calc. for $C_{16}H_{16}Br_2$: C, 52·2; H, 4·4; Br, 43·4%).

Huang-Minlon Reduction of 2 : 2′-*Diacetyldiphenyl*.—2 : 2′-Diacetyldiphenyl (20 g.), powdered sodium hydroxide (34 g.), 85% aqueous hydrazine hydrate (34 c.c.), and triethylene glycol (500 c.c.) were heated together under reflux for 2 hr. Water and excess of hydrazine hydrate were removed by distillation until the temperature reached 195°. Heating under reflux was then resumed for 4 hr. The mixture was poured into water and extracted with ether, and the ethereal solution washed and dried (K_2CO_3). The ether was removed and the residual oil distilled under reduced pressure, giving fraction 1, b. p. 140—150°/1 mm. (15·8 g.), and fraction 2, b. p. 160—168°/1 mm. (2·9 g.). Both fractions solidified and were crystallised separately from methanol, giving the main product (12·3 g.), 9 : 10-dimethylphenanthrene (0·2 g., from fraction 2), and a residual oil. Recrystallisation of the main product from methanol gave pure 2-*methyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-1 : 3 : 5-*triene*, m. p. 49·5—50·5° (10 g., 40%) (Found: C, 93·1; H, 7·0. $C_{16}H_{14}$ requires C, 93·2; H, 6·8%) (0·4052 g. of hydrocarbon required 33·3 c.c. of 0·1123N-bromine, equiv. to 0·95 double bond). The residue in the distillation flask was extracted with benzene, and the solution concentrated and treated with a solution of picric acid in benzene. 9 : 10-Dimethylphenanthrene picrate (0·5 g.) separated.

2-*Methyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-3 : 5-*diene*.—The above triene (7·5 g.) in glacial acetic acid (35 c.c.) was shaken with hydrogen in the presence of palladium (1·0 g.). The product was isolated in the usual manner and distilled twice under reduced pressure. The *diene* was obtained as an oil, b. p. 120°/1 mm., n_D^{25} 1·6102 (Found: C, 92·3; H, 8·0. $C_{16}H_{16}$ requires C, 92·3; H, 7·7%).

Oxidation of 2-*Methyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-1 : 3 : 5-*triene*.—(a) *With selenium dioxide*. The triene (0·513 g.) in xylene (2·5 c.c.) was heated under reflux with selenium dioxide (0·304 g.) for 5½ hr. The solution was filtered and the xylene distilled off. The residue was dissolved in ether and benzene and washed with water and alkali. The solvents were removed; on further heating the residue began to decompose and could not be distilled. It was extracted with alcohol and treated with 2 : 4-dinitrophenylhydrazine reagent. 2-*Methyl*-7-*oxo*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-1 : 3 : 5-*triene* 2 : 4-*dinitrophenylhydrazone* crystallised from benzene–light petroleum and had m. p. 252° (decomp.) (Found: C, 66·3; H, 4·4; N, 14·0. $C_{22}H_{16}O_4N_4$ requires C, 66·0; H, 4·0; N, 14·0%).

(b) *With sodium dichromate in acetic acid.* The triene (1·6 g., 1 mol.) in acetic acid (7·5 c.c.), and sodium dichromate (7·0 g., 3 mol.) in acetic acid (20 c.c.), were heated together on a steam-bath for 1¾ hr. The solution was poured into water and extracted with chloroform. The chloroform solution was shaken with aqueous sodium carbonate, washed with water, and dried (Na_2SO_4), and the solvent distilled off. The residue was treated with a little benzene, and a yellow solid filtered off. It had m. p. and mixed m. p. with phenanthraquinone 208—209° and with *o*-phenylenediamine gave the quinoxaline, m. p. 222—223°, mixed m. p. 223—224°. The benzene solution, after removal of the phenanthraquinone, was diluted with benzene and light petroleum and passed through alumina. The column was eluted with the same solvent and finally with benzene. Concentration of the eluate gave a gum which later became crystalline. After several crystallisations from *cyclo*hexane it had m. p. 80—83°, not depressed on admixture with 2-acetyl-2′-formyldiphenyl (see below). The sodium carbonate washings (of the original chloroform solution) were acidified and gave a gum which later solidified. After several crystallisations (from aqueous alcohol and *cyclo*hexane) it had m. p. 120—121° (Found: C, 74·8; H, 5·0. Calc. for $C_{15}H_{12}O_3$: C, 75·0; H, 5·0%). Lucien and Taurins [16] give m. p. 121—122 for 2′-acetyldiphenyl-2-carboxylic acid.

Oxidation of 2 : 2′-Divinyldiphenyl.—The hydrocarbon (1·0 g., 1 mol.) in acetic acid (5 c.c.), and sodium dichromate (4·4 g., 3 mol.) in acetic acid (13 c.c.), were heated together on a steam-bath for 1¾ hr. Evolution of a gas (presumably carbon dioxide) began after a few min. The cooled solution was poured into water and extracted with chloroform. The extract was washed with aqueous sodium carbonate and water, dried and evaporated. The semi-solid residue was treated with a little benzene and filtered. The solid was crystallised from benzene and then had m. p. and mixed m. p. with phenanthraquinone 209°. The quinoxaline had m. p. and mixed m. p. 224—225°.

3 : 8-*Dimethyl*-4 : 5-6 : 7-*dibenzo*-1 : 2-*diazocine* (IX).—A solution of 2 : 2′-diacetyldiphenyl (5 g.) and 85% aqueous hydrazine hydrate (2·5 c.c.) in ethanol (20 c.c.) was kept at *ca.* 60—40° overnight. On cooling, the solution deposited prisms and, after the addition of water, a mixture of needles and prisms. A sticky third crop was obtained on addition of more water. The crops were combined and warmed with dilute hydrochloric acid and filtered. The insoluble needles were 9 : 10-dimethylphenanthrene (m. p. and mixed m. p. 144—145° after crystallisation) (*ca.* 0·2 g.). Addition of aqueous ammonia to the filtrate precipitated the *azine* (IX); it crystallised from aqueous ethanol in pointed prisms, m. p. 167—168° (2·6 g., 53%) (Found: C, 82·0; H, 6·2; N, 11·8. $C_{14}H_{14}N_2$ requires C, 82·0; H, 6·0; N, 12·0%). In other preparations the solution was boiled under reflux for several hours; rather more dimethylphenanthrene and less azine were then obtained.

Reactions of the Azine (IX).—(*a*) Dilute sulphuric acid (15 c.c.) and the azine (0·3 g.) were boiled under reflux for 1 hr. Oily drops were present and solidified on cooling. The solid was extracted with alcohol (a little did not dissolve); the solution deposited 2 : 2′-diacetyldiphenyl, m. p. and mixed m. p. 91—93°. (*b*) The azine (0·6 g.), powdered sodium hydroxide (0·7 g.), and triethylene glycol (11 c.c.) were heated together at 195° for 3½ hr. Water and hydrochloric acid were added to the cooled mixture. A solid (0·5 g.) was collected (m. p. *ca.* 125—135°). After crystallisation from ethanol it had m. p. 143—145° (mixed m. p. with 9 : 10-dimethylphenanthrene, 143—145°).

2 : 7-*Dihydro*-2 : 2 : 7 : 7-*tetramethyl*-3 : 4-5 : 6-*dibenzoxepin* (XII).—A suspension of the diol (XI) (2 g.) in 4N-sulphuric acid (60 c.c.) was boiled under reflux for 1 hr. Some oxepin collected in the condenser. The contents of condenser and flask were extracted with ether, and the ethereal solution dried (K_2CO_3) and evaporated. The *oxepin* was crystallised once from ethanol and then twice from methanol, forming flat prisms, m. p. 92—93° (slight softening at 87°) (Found: C, 85·5; H, 8·1. $C_{18}H_{20}O$ requires C, 85·7; H, 8·0%). The oxepin is formed as a by-product in the preparation of the tetramethyl-diol if all traces of acid are not removed before distillation of the ether.

2 : 7 : 7-*Trimethyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-1 : 3 : 5-*triene* (XIII).—(*a*) A mixture of 2 : 2′-di-(1-hydroxy-1-methylethyl)diphenyl (10 g.) and naphthalene-2-sulphonic acid (0·1 g.) was heated at 140° for ¼ hr. The mixture was treated with hot water. On cooling, the cyclic *hydrocarbon* solidified and, after crystallisation successively from ethanol, light petroleum (b. p. 40—60°), and ethanol, had m. p. 100—101° (Found: C, 92·4; H, 7·7. $C_{18}H_{18}$ requires C, 92·3; H, 7·7%) (Cook and Turner found m. p. 97—98° for what must have been the same hydrocarbon, although they regarded it as 2 : 2′-di*iso*propenyldiphenyl).

[16] Lucien and Taurins, *Canad. J. Chem.*, 1952, **30**, 208.

(*b*) A suspension of the diol (XI) or of the oxepin in hydrobromic acid (*d* 1·49) was boiled under reflux for 1 hr. On cooling, the hydrocarbon became a crystalline cake, which after recrystallisation from ethanol, had m. p. 100—101°.

2 : 2 : 7-*Trimethyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-3 : 5-*diene* (XIV).—A solution of 2 : 7 : 7-trimethyl-3 : 4-5 : 6-dibenzo*cyclo*hepta-1 : 3 : 5-triene (10 g.) in a mixture of glacial acetic acid and ethyl acetate was shaken in hydrogen under pressure in presence of Adams's platinum oxide for several hours. After removal of the catalyst the ethyl acetate was distilled off and water was added to the acetic acid solution. The solid which separated (9·5 g.) was crystallised twice from ethanol; it formed stout rectangular prisms, m. p. 69—71° (Found: C, 91·5; H, 8·5. $C_{16}H_{16}$ requires C, 91·5; H, 8·5%).

2 : 2′-*Diisopropenyldiphenyl* (X).—The diol (XI) (5 g.) was boiled (320°) in a large test-tube, and a little copper bronze and activated alumina were added. Vigorous dehydration occurred and the b. p. dropped within 10 min. to 295°. The cooled mixture was extracted with ether, the ether evaporated, and the residue distilled. 2 : 2′-*Diisopropenyldiphenyl* (3 g.) had b. p. 136°/5 mm., n_D^{21} 1·5890 (Found: C, 92·1; H, 7·8. $C_{18}H_{18}$ requires C, 92·3; H, 7·7%). A little of the oxepin was also isolated.

Hydrogenation of 2 : 2′-*Diisopropenyldiphenyl*.—A glacial acetic acid solution of the diene was shaken in hydrogen in presence of Adams's platinum oxide for 1 hr. The catalyst was removed and water added to the solution. The solid which separated, after being crystallised from ethanol, had m. p. 67—68° alone or when mixed with 2 : 2′-di*iso*propyldiphenyl.[1]

Action of Hydrobromic Acid on 2 : 2′-*Diisopropenyldiphenyl*.—A mixture of the diene (1·3 g.) with hydrobromic acid (20 c.c.; *d* 1·49) was boiled for 1½ hr., then cooled and extracted with ether. Evaporation of the ether gave a solid which after being crystallised twice from ethanol had m. p. 100—101° alone or when mixed with the cyclic triene (XIII).

Action of 50% *Sulphuric Acid on* 2 : 2′-*Diisopropenyldiphenyl*.—A mixture of the diene (1·0 g.) with 50% (w/w) sulphuric acid (18 c.c.) was boiled for 5 hr., then cooled and extracted with ether. Evaporation of the ether followed by crystallisation from ethanol gave the cyclic triene (0·5 g.), m. p. 100—101°.

Action of Hydrobromic Acid on 2 : 2′-*Divinyldiphenyl*.—A mixture of the hydrocarbon (0·5 g.) and hydrobromic acid (10 c.c.; *d* 1·49) was boiled for 1½ hr., then cooled, and the oil was washed with water and aqueous sodium carbonate. It solidified and after 3 crystallisations from methanol had m. p. 85—89°. The mixed m. p. with 2 : 2′-di-(1-bromoethyl)diphenyl was 85—90°.

Oxidation of 2 : 7 : 7-*Trimethyl*-3 : 4-5 : 6-*dibenzo*cyclo*hepta*-1 : 3 : 5-*triene* (XIII).—The triene (1·1 g., 1 mol.) in acetic acid (5 c.c.) and sodium dichromate (5·6 g., 4 mols.) in acetic acid (17 c.c.) were heated together on a steam-bath for 1½ hr. The solution was poured into water and extracted with chloroform. The chloroform solution was shaken with aqueous sodium carbonate, washed with water, dried (Na_2SO_4), and evaporated. The residue was extracted with light petroleum (b. p. 40—60°). The small insoluble orange residue was dissolved in ethanol and treated with an ethanolic solution of *o*-phenylenediamine. The precipitated quinoxaline, after crystallisation from benzene, had m. p. 222—223°, not depressed on admixture with the quinoxaline from phenanthraquinone. The light petroleum extract deposited a gum which, after treatment with *cyclo*hexane, followed by recrystallisation, yielded 2-*acetyl*-2′-*formyldiphenyl*, m. p. 84° (Found: C, 80·1; H, 5·5. $C_{15}H_{12}O_2$ requires C, 80·3; H, 5·4%). Cook *et al.*[10] obtained this aldehyde as a gum by the oxidation of 9-methylphenanthrene. Dinitrophenylhydrazone formation was accompanied by cyclisation; 7-oxo-3 : 4-5 : 6-dibenzo*cyclo*hepta-1 : 3 : 5-triene 2 : 4-dinitrophenylhydrazone, m. p. *ca.* 208° (decomp.), was isolated (Found: C, 65·2; H, 3·5; N, 13·8. Calc. for $C_{21}H_{14}O_4N_4$: C, 65·3; H, 3·65; N, 14·5%) (Cook *et al.*[9] give m. p. 231—232°). The sodium carbonate washings (of the original chloroform solution) were acidified and gave a gum from which two impure crystalline acids were eventually isolated. Quantities were too small for further investigation.

We thank Mr. R. K. Mitchell for assistance with the large-scale preparations of diacetyldiphenyl, the Central Research Funds Committee of the University for a grant for the purchase of a spectrophotometer, and Imperial Chemical Industries Limited for a grant.

Bedford College, University of London. [*Received, March 29th*, 1956.]

674. *The Structure of the Extracellular Polysaccharide of* Aerobacter aerogenes A3 (S1) (*Klebsiella Type* 54).

By G. O. Aspinall, R. S. P. Jamieson, and J. F. Wilkinson.

Preliminary studies have shown that the extracellular slime polysaccharide of *Aerobacter aerogenes* A3 (S1) possesses a highly branched molecular structure containing residues of D-glucose, L-fucose, and glucuronic acid. Cellobiose has been identified amongst the products of partial acid hydrolysis. A number of methylated sugars, including 2 : 3 : 4 : 6-tetra-*O*-methyl-D-glucose, 2 : 3-di-*O*-methyl-D-glucose, 3 : 5-di-*O*-methyl-L-fucose, and 2-*O*-methyl-L-fucose, have been characterised from the products of hydrolysis of the methylated polysaccharide.

In a previous study [1] it was shown that the extracellular slime polysaccharide of *Aerobacter aerogenes* A3 (S1) (Klebsiella Type 54), isolated as the free acid, was composed of three sugar residues, D-glucose (46%), L-fucose (10%), and an unidentified uronic acid (27%), together with traces of galactose (*ca.* 2%). It was also shown that the composition of the polysaccharide was independent of the carbon source, when the bacterium was grown in the presence of a variety of carbohydrates as the sole carbon and energy source. A start has now been made in the determination of the molecular structure.

The nature of the uronic acid residue was established as glucuronic acid by the following observations: (*a*) glucurone was detected by paper chromatography when the polysaccharide was hydrolysed with 4N-hydrochloric acid; (*b*) glucose was the only hexose detected in significant amount when the polysaccharide was hydrolysed after reduction of the acidic residues (as methyl esters) with potassium borohydride; and (*c*) estimation of the glucose and fucose formed on hydrolysis of the polysaccharide, before and after reduction of the uronic acid to hexose residues, showed that the ratio (by weight) of glucose to fucose increased from 4·0 : 1 to 5·8 : 1. Although the value obtained for the ratio of glucose to fucose given on direct hydrolysis of the polysaccharide was slightly different from that obtained in the previous investigation,[1] it is clear that treatment of the uronic acid residues (as methyl ester) with potassium borohydride has resulted in the formation of further glucose residues; it is probable, however, that reduction with this reagent (cf. sodium borohydride [2]) was not complete.

Chromatographic examination of the products of graded hydrolysis of the polysaccharide showed that some of the glucose was released readily and that shortly afterwards cellobiose could also be detected. On prolonged heating, fucose, traces of galactose, and more glucose were formed. On a larger scale the products of partial acid hydrolysis were separated chromatographically, and cellobiose and D-glucose were identified as crystalline derivatives. The partially degraded polysaccharide yielded L-fucose and more D-glucose on more vigorous hydrolysis, together with a mixture of acidic oligosaccharides, all of which gave glucose, fucose, and glucurone after drastic hydrolysis.

The polysaccharide was methylated by Fear and Menzies's method.[3] The methylated sugars obtained on hydrolysis of the methylated polysaccharide were fractionated chromatographically on cellulose,[4] and the following were characterised as crystalline derivatives: 2 : 3 : 4 : 6-tetra-*O*-methyl-D-glucose, 2 : 3-di-*O*-methyl-D-glucose, 3 : 5-di-*O*-methyl-L-fucose, and 2-*O*-methyl-L-fucose. Evidence was also obtained for the presence of a trace of 2 : 3 : 4-tri-*O*-methyl-D-glucose, a mixture of tri-*O*-methyl-D-glucoses (including the 2 : 3 : 6-isomer, as shown by the downward change in rotation in methanolic hydrogen chloride), a mixture of 2 : 6- and 3 : 6-di-*O*-methyl-D-glucoses, and a mixture of mono-*O*-methylglucoses (including the 2- and the 3-methyl ether). In addition, a complex acidic fraction was obtained from this hydrolysis, but attempts to isolate individual components failed. After hydrolysis under drastic conditions, chromatography showed tri-, di-, and

[1] Wilkinson, Dudman, and Aspinall, *Biochem. J.*, 1955, **59**, 446.
[2] Wolfrom and Anno, *J. Amer. Chem. Soc.*, 1952, **74**, 5583.
[3] Fear and Menzies, *J.*, 1926, 937.
[4] Hough, Jones, and Wadman, *J.*, 1949, 2511.

mono-*O*-methyl-uronic acids to be present; furthermore, after reduction of the acidic fraction with lithium aluminium hydride, hydrolysis yielded sugars travelling on the chromatogram at the same rate as tri-, di-, and mono-*O*-methylglucoses.

The previously unknown sugar 3 : 5-di-*O*-methyl-L-fucose was obtained crystalline, and its structure was established from the following observations: (*a*) demethylation showed the sugar to be a derivative of fucose; (*b*) the derived di-*O*-methyl-L-fuconolactone underwent hydrolysis at a rate characteristic of γ-lactones, and the sign of the optical rotation, according to Hudson's lactone rule,[5] was only consistent with that of a 1 : 4-lactone; (*c*) the consumption of 1 mol. of periodate by the sugar suggested that the sugar was the 3 : 5-dimethyl ether rather than the 2 : 5-dimethyl ether of L-fucose, and the absence of a methoxyl group at $C_{(2)}$ was confirmed, as the derived di-*O*-methyl-L-fuconamide gave a positive Weerman test.

It is now clear that the molecule is highly branched and that the following sugar residues are definitely present:

Gp 1 . . . ., ... 4 *Gp* 1 . . . ., ... 2 Fuc*f* 1 . . . ., ... 4(or 5) Fuc 1 . . . .
3
.
.
.

(*Gp* = D-glucopyranose, Fuc*f* = L-fucofuranose)

The isolation of cellobiose on graded hydrolysis of the polysaccharide shows that adjacent β-1 : 4-linked D-glucopyranose residues are present. It is not clear, however, which of the dimethyl and monoethyl ethers of D-glucose have structural significance as arising from branching points and which have arisen from incomplete methylation of the polysaccharide and/or demethylation during hydrolysis. On the other hand, it is certain that some of the L-fucose residues are branching points in the molecule as 2-*O*-methyl-L-fucose cannot have been formed from the incomplete methylation of 3 : 5-di-*O*-methyl-L-fucose, the only other methyl-L-fucose isolated. The release of 1 mole of formic acid per 3 sugar residues on periodate oxidation of the polysaccharide suggests the presence of a high proportion of non-reducing terminal groups and/or 1 : 6-linked D-glucose residues. In view of the small amount of 2 : 3 : 4 : 6-tetra-*O*-methyl-D-glucose isolated on hydrolysis of the methylated polysaccharide and in the absence of more than traces of 2 : 3 : 4-tri-*O*-methyl-D-glucose, it seems probable that some of the glucuronic acid residues may occupy terminal positions in the molecule.

Experimental

Paper partition chromatography was carried out on Whatman No. 1 filter paper with the solvent systems: (*A*) butan-1-ol–benzene–pyridine–water (5 : 1 : 3 : 3; v/v; top layer); (*B*) butan-1-ol–ethanol–water (4 : 1 : 5; v/v; top layer); (*C*) butan-1-ol–acetic acid–water (4 : 1 : 5; v/v; top layer); (*D*) butan-1-ol saturated with 5% aqueous formic acid.

Isolation and Examination of the Extracellular Polysaccharide.—The organism was grown in a buffered medium (pH 7·3) containing D-glucose as sole carbon source, and the extracellular polysaccharide was isolated as the free acid as described by Wilkinson, Dudman, and Aspinall.[1] The polysaccharide had an equivalent of 683 (by titration), corresponding to 25·8% uronic anhydride (compare 29·0% uronic anhydride previously found). The uronic anhydride content was also determined by Kaye and Kent's method [6] after the polysaccharide had been converted into the corresponding methyl ester by heating with methanolic hydrogen chloride, a value of 25·5% being obtained. Direct reaction of the polysaccharide with the same reagents showed that ester and lactone groups were absent and no methoxyl content was detected. When the polysaccharide was hydrolysed and the hydrolysate was examined chromatographically, the three sugars described previously (glucose, fucose, and galactose) were detected, but after hydrolysis with 4N-hydrochloric acid glucurone was also found.

Hydrolysis of the Polysaccharide after Reduction with Potassium Borohydride.—The polysaccharide (18·3 mg.) was heated in a sealed tube with 98% formic acid (2 c.c.) at 100° for 24 hr., the formic acid was removed *in vacuo*, L-rhamnose (5·45 mg.) was added, and the mixture was refluxed with methanolic 1% hydrogen chloride (5 c.c.) for 4 hr. After neutralisation with silver carbonate the product was dissolved in water (2 c.c.), and the solution was

[5] Hudson, *J. Amer. Chem. Soc.*, 1910, **32**, 338.
[6] Kaye and Kent, *J.*, 1953, 79.

added dropwise to a solution of potassium borohydride (20 mg.) in water (2 c.c.). After 20 min. the excess of borohydride was destroyed by dilute acetic acid, and the solution was de-ionised with Amberlite resins IR-120(H) and IR-4B(OH). The reduction product was hydrolysed with N-hydrochloric acid (4 c.c.) at 100° for 4 hr. and neutralised, and the ratios of the sugars obtained were determined. A second sample of polysaccharide was treated similarly except that the reduction with potassium borohydride was omitted.

The results showed that the ratio of glucose to fucose was 5·8 : 1 in the former case and 4·0 : 1 when the reduction was omitted. The ratios of fucose to the reference sugar, rhamnose, were the same in both cases.

Graded Hydrolysis of the Polysaccharide.—Chromatographic examination of the products of the hydrolysis of the polysaccharide with hot 0·5N-hydrochloric acid, showed that glucose was released after 5 min. and that after 30 min. a disaccharide travelling on the chromatogram at the same rate as cellobiose was observed. On further heating fucose and traces of galactose were also released.

The polysaccharide (2 g.) was heated at 100° with 0·5N-sulphuric acid (100 c.c.) for 30 min. The cooled solution was neutralised with barium carbonate, and the filtrate was reduced in volume to 10 c.c. and poured into acetone (20 c.c.). The precipitate was redissolved in water, and the solution de-ionised with Amberlite resin IR-120(H) and taken to dryness to give fraction *X* (0·84 g.). The supernatant liquid remaining after the acetone precipitation was taken to dryness to give fraction *Y* (0·70 g.). Most (0·67 g.) of this fraction was separated on filter sheets by using solvent *A* to give small fractions containing sugars travelling on the chromatogram at the same rate as glucose, galactose, and cellobiose, whilst most of the material, fraction *Y*(i) (0·53 g.), remained at the starting line. D-Glucose and cellobiose were identified by conversion into 1 : 2 : 3 : 4 : 6-penta-*O*-acetyl-β-D-glucose, m. p. 126—128° and mixed m. p. 127—130°, and cellobiose α-octa-acetate, m. p. and mixed m. p. 220—222°, respectively.

Chromatographic examination of fractions *X* and *Y*(i) in solvent *C* showed them to contain similar mixtures of acidic oligosaccharides. It was not possible completely to separate the components, but all the fractions examined yielded on further hydrolysis D-glucose, L-fucose (identified as the toluene-*p*-sulphonylhydrazone, m. p. and mixed m. p. 167—170°), galactose (trace), and glucurone. When the acidic fractions were reduced by treatment of the corresponding methyl ester methyl glycosides with potassium borohydride, the hydrolysis products contained glucose, fucose, and galactose (trace).

Methylation of the Polysaccharide.—The polysaccharide (5 g.) was converted into its thallium derivative which was heated with methyl iodide, and the product was further methylated by three treatments with thallous ethoxide and methyl iodide; this gave a methylated polysaccharide (3·7 g.) (Found: OMe, 39·6%), whose methoxyl content could not be raised on further treatments with thallous ethoxide and methyl iodide.

Hydrolysis of the Methylated Polysaccharide and Separation of the Methylated Sugars.—The methylated polysaccharide (3·2 g.) was hydrolysed successively with methanolic 1% hydrogen chloride (200 c.c.) for 17 hr. (constant rotation) and with hydrochloric acid (200 c.c.; 0·5N) for 10·5 hr. (constant rotation). The solution was neutralised with silver carbonate, the silver ions were removed with hydrogen sulphide, and the acidic components were converted into barium salts by treatment with barium carbonate. The solution was evaporated to a dark brown glass (2·8 g.).

The hydrolysate was dissolved in the minimum quantity of water, and the resulting syrup was allowed to soak into the top of a column (60 × 3 cm.) of cellulose. Elution of the column with light petroleum (b. p. 100—120°)–butan-1-ol (7 : 3; later 1 : 1), saturated with water, butan-1-ol partly saturated with water, and water gave nine fractions.

Fraction 1. The syrup (8 mg.) had $[\alpha]_D^{20}$ +87° (*c*, 0·4 in H_2O) and travelled on the chromatogram at the same rate as 2 : 3 : 4 : 6-tetra-*O*-methyl-D-glucose. The sugar was identified as this compound by conversion into the aniline derivative, m. p. 123—124° and mixed m. p. 125—127° (with an authentic sample, m. p. 128—129°). In a separate series of experiments 2 : 3 : 4 : 6-tetra-*O*-methyl-D-glucose crystallised, had m. p. and mixed m. p. 84—86°, and its *X*-ray powder photograph (courtesy of Dr. C. A. Beevers) was identical with that of an authentic specimen.

Fraction 2. The syrup (5 mg.) had $[\alpha]_D^{20}$ +63°, travelled on the chromatogram at the same rate as 2 : 3 : 4-tri-*O*-methyl-D-glucose (R_G 0·87), and gave glucose on demethylation (Found: OMe, 41·2. Calc. for $C_9H_{18}O_6$: OMe, 41·9%).

Fraction 3. Chromatographic examination of the syrup (122 mg.) showed the presence of two components travelling at the rates of 2 : 3 : 6- and 2 : 4 : 6-tri-*O*-methyl-D-glucose

(R_G 0·81—0·83) (Found: OMe, 41·6. Calc. for $C_9H_{16}O_6$: OMe, 41·9%). Demethylation gave only glucose and the presence of 2 : 3 : 6-tri-*O*-methyl-D-glucose in the mixture was shown by the fall in rotation in methanolic 2% hydrogen chloride at room temperature {$[\alpha]_D^{20}$ +73° ⟶ +35° (26 hr., const.; *c*, 1·8)}.

Fraction 4. The syrup (76 mg.) was chromatographically homogeneous (R_G 0·79—0·80 in solvent *B*), gave a green colour with aniline oxalate, had $[\alpha]_D^{20}$ −72° ⟶ −67° (24 hr., const.; *c*, 1·5 in H_2O), and yielded fucose on demethylation with hydriodic acid (Found: OMe, 32·2. Calc. for a 6-deoxy-di-*O*-methylhexose, $C_8H_{16}O_5$: OMe, 32·3%). The derived 6-deoxy-di-*O*-methylhexonolactone had $[\alpha]_D^{20}$ +66° ⟶ +51° (7 days, const.; *c*, 0·66 in H_2O) and was converted into a 6-deoxy-di-*O*-methylhexonamide, which did not crystallise but yielded hydrazodicarbonamide, m. p. and mixed m. p. 252—254°, when treated with sodium hypochlorite. The original syrup consumed 1·15 moles of periodate per $C_8H_{16}O_5$ unit.

In separate experiments 3 : 5-*di-O-methyl-*L-*fucose* was obtained crystalline; it had m. p. 118—121°, $[\alpha]_D^{20}$ −100° ⟶ −69° (24 hr., const.; *c*, 0·42 in H_2O) (Found: OMe, 32·2. $C_8H_{16}O_5$ requires OMe, 32·3%).

Fraction 5. The syrup (45 mg.) travelled on the chromatogram at the same rate as 2 : 3-di-*O*-methyl-D-glucose and gave glucose on demethylation. The sugar had $[\alpha]_D^{20}$ +64° (equil.; *c*, 0·52 in H_2O) (Found: OMe, 29·7. Calc. for $C_8H_{16}O_6$: OMe, 29·7%), and was identified by conversion into 2 : 3-di-*O*-methyl-*N*-phenyl-D-glucosylamine, m. p. and mixed m. p. 129—131°.

Fraction 6. The syrup (164 mg.) was chromatographically homogeneous (R_G 0·54 in solvent *B*) but the methoxyl content (23·4%) suggested the presence of two components. Fractionation gave an acetone-insoluble fraction 6*a* (43 mg.) and an acetone-soluble fraction 6*b* (121 mg.). Fraction 6*a* was obtained crystalline and yielded fucose on demethylation. The sugar had m. p. 142—145° and mixed m. p. (with 2-*O*-methyl-L-fucose, m. p. 147—149°) 144—148°, $[\alpha]_D^{20}$ −71° (initial) ⟶ −81° (24 hr., const.; *c*, 0·33 in H_2O) (Found: OMe, 17·5. Calc. for $C_7H_{14}O_5$: OMe, 17·4%). Fraction 6*b* yielded glucose on demethylation, travelled on the chromatogram at the same rate as 2 : 6- and/or 3 : 6-di-*O*-methyl-D-glucose, and had $[\alpha]_D$ +60° (equil.; *c*, 2·0 in H_2O). Periodate oxidation of the derived methyl glycosides[7] showed that 83% of the fraction was 2 : 6-di-*O*-methyl-D-glucose. The periodate-oxidised methyl glycosides were hydrolysed, and chromatographic examination showed the presence of 3 : 6-di-*O*-methyl-D-glucose.

Fraction 7. The syrup (97 mg.) travelled on the chromatogram at the same rate as 2 : 6- and/or 3 : 6-di-*O*-methyl-D-glucose in solvent *B* but another component was detected by chromatography in solvent *A*. Fractionation of a portion of the syrup in solvent *A* yielded fraction 7*a* (40 mg.) and fraction 7*b* (4 mg.). Periodate oxidation of the derived methyl glycosides showed fraction 7*a* to contain 80% of 2 : 6-di-*O*-methyl-D-glucose, and hydrolysis of the periodate-oxidised methyl glycosides gave 3 : 6-di-*O*-methylglucose. Fraction 7*b* had R_G 0·50 in solvent *B* (yellow colour with aniline oxalate) and gave glucose on demethylation.

Fraction 8. Chromatographic examination of the syrup (190 mg.) in solvent *A* indicated only one component (R_G 0·20—0·22), but on examination in solvent *B* three substances were shown to be present, one of them travelling at the same rate as L-fucose. A portion of the syrup was oxidised by periodate according to Lemieux and Bauer's[8] procedure; chromatographic examination showed the products to be similar to those formed on oxidation of 2- and 3-*O*-methyl-D-glucose. The two faster components were separated from fucose on filter sheets by using solvent *A* to give fraction 8*a* (64 mg.) which yielded glucose on demethylation (Found: OMe, 16·0. Calc. for $C_7H_{14}O_6$: OMe, 16·0%).

Fraction 9. This fraction (1·30 g.) obtained on elution of the cellulose column with water was present as the barium salt and had equivalent wt. 223. Drastic hydrolysis with 2N-sulphuric acid followed by chromatographic examination in solvent *D* showed that three acidic components, R_G 0·84, 0·58, 0·44 (cherry-red coloration with aniline oxalate), and some neutral sugars were produced. A portion was converted into the methyl ester methyl glycoside, which was reduced with lithium aluminium hydride; hydrolysis of the product yielded sugars travelling on the chromatogram (solvent *B*) at the same rate as tri-, di-, and mono-methylglucoses, together with 3 : 5-di-*O*-methylfucose. An attempt to separate the acidic components by elution from Amberlite resin IRA-400 (acetate form) with increasing concentrations of acetic acid resulted in loss of the sugar acids by adsorption and/or decomposition on the resin.

Periodate Oxidation of the Polysaccharide.—The polysaccharide (154·3 mg.) was dissolved

[7] Bell, *J.*, 1948, 992.

[8] Lemieux and Bauer, *Canad. J. Chem.*, 1953, **31**, 811.

in potassium chloride solution (60 c.c.; 0·56M) and the pH of the solution was adjusted to 6·25. Sodium metaperiodate solution (20 c.c.; 0·20M) was added and the solution was shaken in the dark. Aliquot portions (10 c.c.) were removed from time to time, ethylene glycol (1 c.c.) was added, and the mixture was titrated against 0·108N-sodium hydroxide to pH 6·25 in a stream of nitrogen. After 160 hr. the formic acid released corresponded to 0·34 mole per 162 g. of polysaccharide.

The polysaccharide (101·6 mg.) was dissolved in water (50 c.c.), and sodium metaperiodate solution (50 c.c.; 0·40M) was added. Estimation of the periodate consumed showed that a constant value of 1·28 mole per 162 g. of polysaccharide was reached after 71 hr. Hydrolysis of a sample of the periodate-oxidised polysaccharide showed the presence of glucose and fucose.

The authors thank Professor E. L. Hirst, F.R.S., for his interest and advice, the Department of Scientific and Industrial Research for the award of a Maintenance Allowance (to R. S. P. J.), and Imperial Chemical Industries Limited and the Distillers Company Limited for grants.

DEPARTMENTS OF CHEMISTRY AND BACTERIOLOGY,
UNIVERSITY OF EDINBURGH.

[*Received, April 9th*, 1956.]

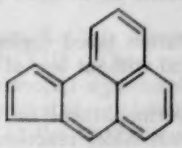
---

675. *The Synthesis of Indeno[2,1-a]perinaphthene.**

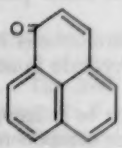
By I. M. AITKEN and D. H. REID.

Indeno[2,1-*a*]perinaphthene (IV) has been synthesised and some of its properties have been studied. The principal findings are: (i) The hydrocarbon is strongly basic; it dissolves reversibly in moderately strong sulphuric acid or anhydrous liquid hydrogen fluoride to form a green cation. (ii) It functions readily as the diene component in Diels–Alder reactions. (iii) Electrophilic substitution takes place readily under mild conditions (the probable position of substitution is discussed). (iv) A new type of reaction by lead tetra-acetate involving intermolecular dehydrogenation is reported.

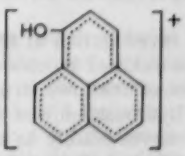
So far as we are aware no compound containing the ring system of *cyclo*penta[*a*]perinaphthene (I) has hitherto been synthesised nor is any known to occur naturally. A five-membered ring is known to possess anionic stability when associated with six π-electrons. Further, perinaphthenone (II) itself, in appropriate circumstances, shows considerable cationic character: *e.g.*, the C=O stretching frequency in the infrared spectrum [1] is unusually low (1637 cm.$^{-1}$); and the ketone is abnormally basic,[2] dissolving reversibly in



(I)



(II)



(III)

concentrated hydrochloric acid. These properties suggest that perinaphthenone has a tendency to become polarised with formation of a stable tricyclic structure of thirteen carbon atoms over which twelve π-electrons are delocalised. This structure exists in the 1-hydroxyperinaphthenylium cation [3] (III) which is present in solutions of perinaphthenone

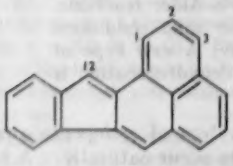
* A preliminary account was read at the 14th Intern. Congr. Pure & Appl. Chem., Zürich, July, 1955.

[1] Cromwell and Hudson, *J. Amer. Chem. Soc.*, 1953, **75**, 872.
[2] Bamberger and Philip, *Annalen*, 1887, **240**, 178; Cook and Hewett, *J.*, 1934, 365.
[3] Boekelheide and Larrabee, *J. Amer. Chem. Soc.*, 1950, **72**, 1245; Clar, "Aromatische Kohlenwasserstoffe," Springer Verlag, Berlin, 1952, 2nd Edn., p. 431.
[4] Reid, Stafford, and Ward, *J.*, 1955, 1193.
[5] Reid, *Angew. Chem.*, 1955, 761.

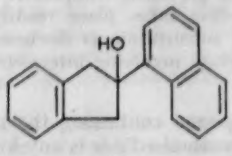
in strong acid. In view of the electronically complementary tendencies of the five-membered ring and the perinaphthene nucleus it was expected that π-electron migration from the perinaphthene moiety to the five-membered ring would prevail to a greater or smaller extent in compounds containing the *cyclo*penta[*a*]perinaphthene ring system. The five-membered ring in such compounds should therefore show considerable nucleophilic reactivity of an order and character found among the azulenes.[4] To test these conclusions we have begun the synthesis and study of compounds containing the *cyclo*penta[*a*]perinaphthene system.[5] In this communication the synthesis of indeno[2,1-*a*]-perinaphthene (IV), a ring homologue of (I), is described, and a preliminary account of some of its properties is given.

Indan-2-one and 1-naphthylmagnesium bromide gave a mixture of the expected tertiary alcohol (V) and its dehydration product (VI). Dehydration of the mixture was completed by boiling formic–acetic acid. The resulting hydrocarbon (VI) displays monotropy. The metastable form tends to crystallise from impure solutions, and fuses to a clear liquid at 77—79°: the melt then solidifies to a mass of colourless plates, constituting the stable modification, which melt at 90—91°.

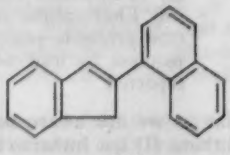
This hydrocarbon condensed with ethyl formate in the presence of potassium methoxide, giving a good yield of the hydroxymethylene compound (VII) which was, however, unstable and could not be isolated pure. Consistently with its tautomeric nature it formed both a benzoate and a 2:4-dinitrophenylhydrazone, which served to characterise it. Owing to its instability, this derivative was cyclised immediately, best by 93% sulphuric acid, the acid concentration being critical. Two highly coloured, benzene-soluble hydrocarbons were obtained in low yield from the cyclisation: one, subsequently shown to be indeno-[2,1-*a*]perinaphthene (IV), was found to be strongly basic—and was removed completely



(IV)



(V)



(VI)

by extraction with 77% sulphuric acid; dilution of the green acid extracts caused its precipitation and it formed reddish-brown leaflets, which gave red solutions in benzene. The second hydrocarbon formed purple-black prisms, which in benzene give crimson solutions.

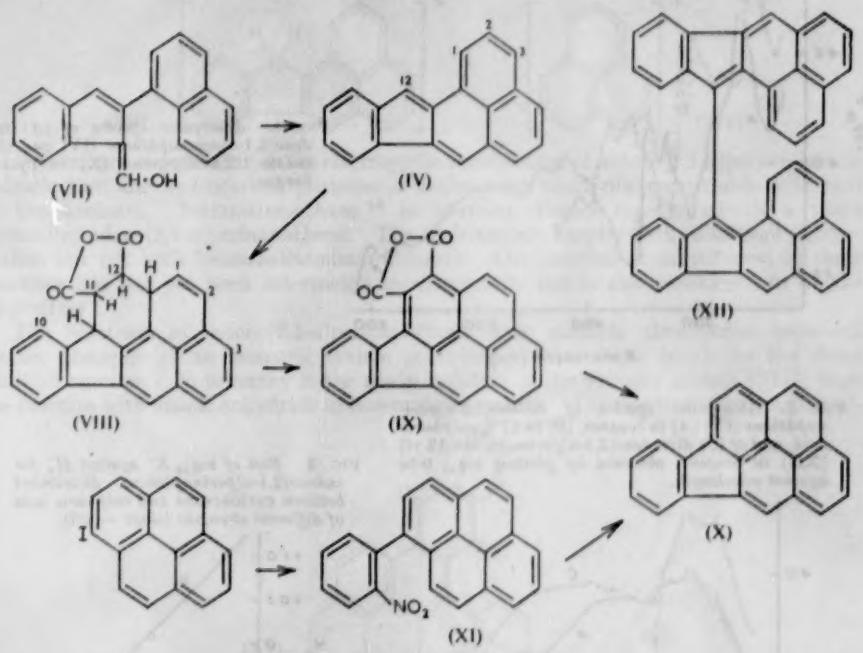
Structural investigation of these hydrocarbons by oxidation failed (indeno[2,1-*a*]perinaphthene was oxidised by chromic anhydride in acetic acid without loss of carbon to an orange diketone of unknown structure).

The basic hydrocarbon was shown to be indeno[2,1-*a*]perinaphthene on the following evidence. It serves readily as the diene component in Diels–Alder reactions: *e.g.*, with maleic anhydride in boiling xylene–acetic acid it gives a colourless adduct (VIII) rapidly and quantitatively. This adduct was dehydrogenated by boiling nitrobenzene and the fully aromatic anhydride (IX) was decarboxylated to the intensely yellow indeno-[1,2,3-*cd*]pyrene (X). Independently, a crossed Ullmann reaction between 1-iodopyrene and *o*-bromonitrobenzene gave 1-*o*-nitrophenylpyrene (XI) which, by successive reduction to the corresponding amine, diazotisation, and treatment with copper bronze, was converted into the same hydrocarbon (X). The synthesis of indeno[1,2,3-*cd*]pyrene from 1-(1-hydroxy-methylene-2-indenyl)naphthalene and from 1-*o*-nitrophenylpyrene is possible only if cyclisation of the former results in formation of a six-membered ring and ring-closure of 1-*o*-aminophenylpyrene involves the formation of a five-membered ring. The basic hydrocarbon must therefore be indeno[2,1-*a*]perinaphthene (IV).

Indeno[2,1-*a*]perinaphthene forms a complex with trinitrobenzene, crystallising in black needles. The absorption spectra (Fig. 1) of indeno[2,1-*a*]perinaphthene (IV) and

indeno[1,2,3-*cd*]pyrene (X) show close correspondence in the number and intensities of band groups and maxima, but the maxima of the former lie at longer wave-lengths.

The constitution of the purple-black, non-basic hydrocarbon has not yet been established with certainty but the tentative assignment of structure (XII) appears justified by the following results: (i) The molecular weight approximates to twice that of indeno[2,1-*a*]-perinaphthene. (ii) The same hydrocarbon is formed in substantial yield when indeno-[2,1-*a*]perinaphthene in benzene is treated at room temperature with lead tetra-acetate. (iii) The purple-black hydrocarbon itself, when subjected to the prolonged action of lead tetra-acetate in boiling benzene, is converted into a high-melting green crystalline solid.



Analytical data for this compound agree well with those required by a monoacetoxy-derivative of (XII). Thus one molecule of the purple-black hydrocarbon contains two nuclei of indeno[2,1-*a*]perinaphthene. The low basicity of the former, which dissolves only in concentrated sulphuric acid, suggests that the indeno[2,1-*a*]perinaphthene nuclei are attached at the 12-positions, as in structure (XII), since for reasons indicated below we associate the basicity of indeno[2,1-*a*]perinaphthene with its 12-position. The visible absorption spectra of the purple-black hydrocarbon and indeno[2,1-*a*]perinaphthene are given in Fig. 2 (the curve there shown for the former was obtained by plotting $\log_{10} 0{\cdot}5\varepsilon$ against wavelength): their close similarity is consistent with structure (XII).

The experimental evidence presented clearly excludes the possibility of the purple-black hydrocarbon's being benzo[*a*]naphtho[1,2-*e*]pentalene, which would be formed by a cyclisation of (VII) involving the 2-position of the naphthalene moiety. No evidence for the formation of such a cyclisation product was found. Blood and Linstead [6] have reported that the closely related 1 : 2-4 : 5-dibenzopentalene is readily polymerised by traces of strong acid. In view of these findings it is unlikely that any benzo[*a*]naphtho-[1,2-*e*]pentalene formed would survive the strongly acid conditions of the cyclisation. The formation of the hydrocarbon (XII) itself under the cyclisation conditions is unusual and

[6] Blood and Linstead, *J.*, 1952, 2263.

no explanation for its formation can be offered. Its formation by the action of lead tetra-acetate on indeno[2,1-*a*]perinaphthene is noteworthy because it constitutes the only case known where the reagent effects intermolecular dehydrogenation of a hydrocarbon.

The most characteristic property of indeno[2,1-*a*]perinaphthene is its high basicity. This compound therefore represents a new class of basic hydrocarbons of which the

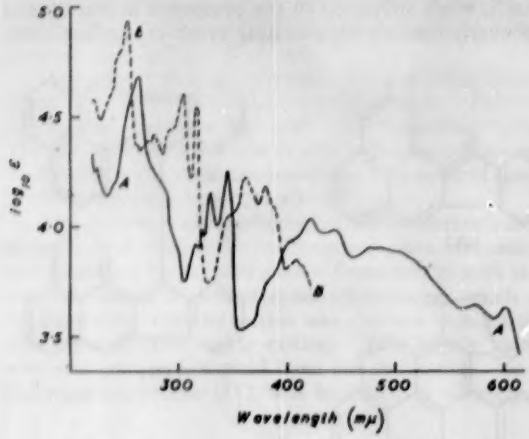


FIG. 1. *Absorption spectra of (A) indeno[2,1-a]perinaphthene* (IV) *and (B) indeno[1,2,3-cd]pyrene* (X) *in cyclohexane.*

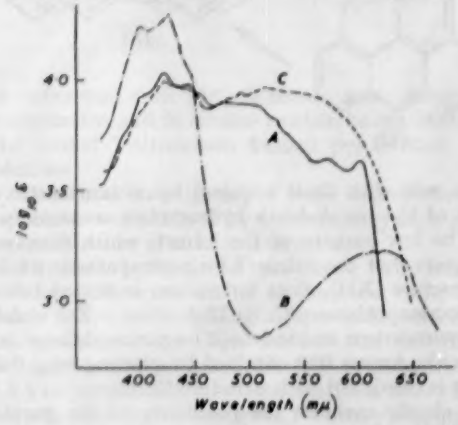


FIG. 2. *Absorption spectra of indeno[2,1-a]perinaphthene* (IV) *(A) in benzene, (B) in 77% sulphuric acid, and of (C) di(indeno[2,1-a]perinaphthen-12-yl)* (XII) *in benzene, obtained by plotting* $\log_{10}$ *0·5ε against wavelength.*

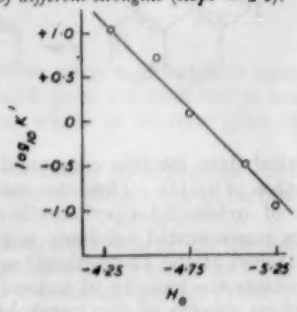


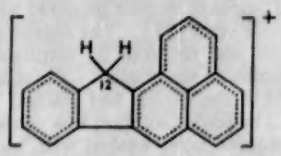
FIG. 3. *Plot of* $\log_{10} K'$ *against* H_0 *for indeno[2,1-a]perinaphthene distributed between cyclohexane and sulphuric acid of different strengths (slope = 2·1).*

simplest member is the still unknown *cyclo*penta[*a*]perinaphthene (I). The hydrocarbon (IV) dissolves reversibly in strong aqueous sulphuric acid or anhydrous liquid hydrogen fluoride, with formation of a green cation. A measure of the basicity was obtained by the procedure of Plattner, Heilbronner, and Weber [7] by which the hydrocarbon was partitioned between *cyclo*hexane and sulphuric acid of different strengths. Fig. 3 discloses that a linear relation exists between $\log_{10} K'$ (where K' is the apparent partition coefficient)

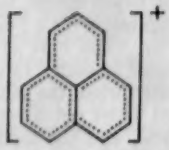
[7] Plattner, Heilbronner, and Weber, *Helv. Chim. Acta*, 1949, **32**, 574.

and the Hammett acidity function H_0,[8] and the slope of the straight line approximates closely to two. This is interpreted [9] as resulting from a salting-in effect on the hydrocarbon base molecules with increasing acidity. The H_0 value found (−4·80) for which K' is unity corresponds to an acid concentration of 64% H_2SO_4 (w/w); this value places indeno[2,1-*a*]perinaphthene alongside the azulenes in order of basicity.[4]

The conjugate acid of indeno[2,1-*a*]perinaphthene is considered to possess structure (XIII) resulting from accession of a proton to $C_{(12)}$. Addition of a proton at this position allows formation, in the perinaphthene moiety, of the π-electron system of the perinaphthenylium cation (XIV) with which considerable stability is associated.



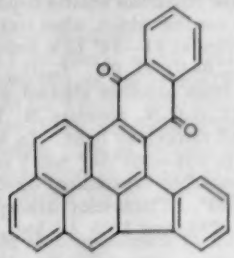
(XIII)



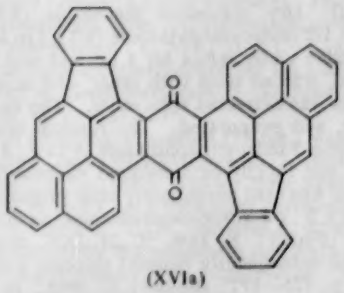
(XIV)

Preliminary experiments on the electrophilic substitution of indeno[2,1-*a*]perinaphthene indicate that the hydrocarbon possesses a nucleophilic reactivity comparable with that of the azulenes. Tetranitromethane [10] in pyridine–ethanol rapidly affords a violet mononitroindeno[2,1-*a*]perinaphthene. The hydrocarbon couples with diazotised *p*-nitroaniline but not with benzenediazonium chloride. The position of substitution in these reactions has not yet been determined experimentally but is also considered to be the 12-position.

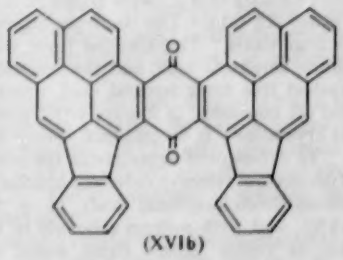
The reactions of indeno[2,1-*a*]perinaphthene with suitable dienophiles represent further examples of an aromatic system providing both multiple bonds for the diene addition reaction. Noteworthy is the ready isolation of the primary adduct (VIII) from the reaction with maleic anhydride in non-oxidising media. The reaction of indeno[2, 1-*a*]-



(XV)



(XVIa)



(XVIb)

perinaphthene with 1 : 4-naphthaquinone in boiling nitrobenzene afforded the expected tetracene derivative (XV). When 1 : 4-benzoquinone was the dienophile a high-melting

[8] Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, 1940, Chap. IX.
[9] Gold and Tye, *J.*, 1952, 2181.
[10] Schmidt and Fischer, *Ber.*, 1920, **53**, 1529.

orange crystalline solid was isolated, resulting from addition of two molecules of the hydrocarbon (IV) to one of 1 : 4-benzoquinone. This product must possess one of the two possible structures (XVIa and b).

Experimental

M. p.s were determined on a Kofler-type heating-stage. Absorption spectra were measured with a Unicam S.P. 500 instrument. Chromatographic purifications were effected on activated alumina.

1-2′-*Indenylnaphthalene* (VI).—A solution of indan-2-one (100 g.) in dry ether (300 ml.) was added during 45 min. to the stirred, ice-cooled Grignard reagent prepared from 1-bromonaphthalene (230 g.) and magnesium (28 g.) in anhydrous ether (1 l.). The resulting solution was boiled under reflux for 1 hr. The bulk of the ether was removed by distillation while anhydrous benzene was introduced at such a rate as to maintain the original volume of the solution. This process was terminated when the temperature of the vapour had reached 76°, and the mixture was thereafter boiled under reflux for 6 hr. The cooled solution was poured into excess of ice-cold 4N-sulphuric acid, and the separated benzene layer washed with water, dried (Na_2SO_4), and evaporated at reduced pressure. The residual dark oil was separated by distillation into two fractions. The first fraction, boiling range 95—140°/18 mm., consisted chiefly of naphthalene with a small quantity of unchanged indan-2-one and was discarded. The second fraction (60·6 g.) was a viscous yellow oil, b. p. 204—213°/0·9 mm. Elementary analysis showed that it consisted approximately of seven parts of 1-(2-hydroxy-2-indanyl)naphthalene (V) and one part of 1-2′-indenylnaphthalene (VI).

The foregoing mixture in glacial acetic acid (300 ml.) and 98% formic acid (250 ml.) was boiled under reflux for 2 hr. The cooled solution was poured into water and the precipitated oil was taken up in ether. The ether extract was washed successively with water (four times), aqueous sodium hydroxide (twice), and again with water, and finally dried (Na_2SO_4). Evaporation of the solvent left a yellow oil which was dissolved in light petroleum–benzene (8 : 1) before filtration through a column (9 × 4·2 cm.). A yellow, strongly adsorbed impurity was retained at the top of the column. The almost colourless eluates deposited the *hydrocarbon* (VI) (46·1 g.) in its metastable form as colourless needles which, after recrystallisation from light petroleum, melted at 77—79°. The melt solidifies at 81—84° to a mass of colourless plates which subsequently melt at 90—91° (Found: C, 94·0; H, 6·0. $C_{19}H_{14}$ requires C, 94·2; H, 5·8%). The *trinitrobenzene complex* crystallised from absolute ethanol as orange elongated prisms, m. p. 142—143° (Found: 12·4. $C_{19}H_{14},C_6H_3O_6N_3$ requires N, 12·6%). Solutions of the hydrocarbon fluoresce blue in daylight and ultraviolet light. In a subsequent experiment the crude hydrocarbon was first distilled (b. p. 184—187°/0·7 mm.) before filtration through a column. The stable modification of the hydrocarbon crystallised directly from the concentrated eluates as colourless plates, m. p. 90·5—91°. Ultraviolet absorption spectrum (in *cyclo*hexane): $\lambda_{max.}$ 3100, 2610, 2545, 2490, 2430, 2235, and 2205 Å; $\log_{10}\varepsilon$ 4·19, 4·22, 4·31, 4·32, 4·39, 4·70, and 4·63.

1-(1-*Hydroxymethylene*-2-*indenyl*)*naphthalene* (VII).—Dry potassium methoxide (3·2 g.) and ethyl formate (3·3 g.) were added to a solution of 1-2′-indenylnaphthalene (9·7 g.) in anhydrous ether (75 ml.). The resulting mixture was boiled under reflux for 4 hr. and was then poured into water. The alkaline layer was removed, washed once with ether, and acidified with dilute sulphuric acid, and the resulting emulsion was extracted with ether. The extract was washed free from mineral acid, dried (Na_2SO_4), and evaporated. The residual orange-coloured oil, consisting of impure 1-(1-hydroxymethylene-2-indenyl)naphthalene (8·75 g., 81%), did not crystallise; it decomposed slowly on storage and rapidly on attempted vacuum-distillation. In subsequent experiments the crude material was used immediately after preparation. 1-(1-Hydroxymethylene-2-indenyl)naphthalene forms a 2 : 4-*dinitrophenylhydrazone*, as orange-red prisms (from propionic acid), m. p. 242—244° (Found: N, 11·9. $C_{26}H_{18}O_4N_4$ requires N, 12·4%), and with sodium ethoxide in ethanol and subsequently benzoyl chloride yields a *benzoate*, as yellow prisms (from acetic acid), m. p. 175—177° (Found: C, 86·3; H, 4·9. $C_{27}H_{18}O_2$ requires C, 86·6; H, 4·8%).

Ring-closure of 1-(1-*Hydroxymethylene*-2-*indenyl*)*naphthalene*.—A cold mixture of 98% sulphuric acid (100 ml.) and water (10 ml.) was added to a solution of crude 1-(1-hydroxymethylene-2-indenyl)naphthalene (4·3 g.) in benzene (12 ml.) contained in a 250 ml. round-bottomed flask. The mixture was at once shaken vigorously in the stoppered flask for 45 sec. and was then poured on crushed ice (250 g.) in water (1 l.). The mixtures obtained from two

such cyclisation experiments were combined and filtered, and the brown residue was washed successively with water (1 l.), saturated sodium hydrogen carbonate solution (500 ml.), and again with water (250 ml.). The residue was dried at reduced pressure over phosphoric oxide and extracted (Soxhlet) with benzene (500 ml.) until no more coloured material passed into solution. The benzene extract was washed with 10% aqueous sodium hydroxide (twice), then with water, and dried (Na_2SO_4). The solution was concentrated to 100 ml. before filtration through a column (10 × 4·2 cm.) with benzene as eluant. A brown, strongly adsorbed band of organic debris remained at the top of the column. The deep red eluates were concentrated to 500 ml. and extracted with 77% sulphuric acid (3 × 300 ml.). The acid extracts were washed with benzene before dilution with ice-cold water (4 l.). The precipitated brown solid was extracted with ether, and the deep red extract was freed from acid by washing with water and aqueous sodium hydroxide before drying (K_2CO_3) and concentration. The partly crystalline residue was purified by chromatography with benzene as solvent and developer. Evaporation of the eluates to small volume gave *indeno*[2,1-*a*]*perinaphthene* (IV) (710 mg.) as reddish-brown leaflets, m. p. 210—211° (with sublimation) [Found: C, 95·1; H, 4·9%; *M* (Rast), 243. $C_{20}H_{12}$ requires C, 95·2; H, 4·8%; *M*, 252]. The *trinitrobenzene complex* crystallised from absolute ethanol as black needles, m. p. 175—176° (Found: N, 8·7. $C_{20}H_{12},C_6H_3O_6N_3$ requires N, 9·0%). The hydrocarbon, when dissolved in strong acid solutions (77% sulphuric acid or anhydrous liquid hydrogen fluoride), undergoes no appreciable decomposition even after several days.

The benzene solution from which indeno[2,1-*a*]perinaphthene had been removed by extraction with sulphuric acid was washed free from acid and dried (K_2CO_3) before concentration. Purification of the residue was accomplished by controlled elution with benzene–light petroleum (3 : 2) after adsorption from benzene on a column (9 × 2·7 cm.). The crimson-red eluates on concentration to low volume deposited *di*(*indeno*[2,1-a]*perinaphthen*-12-*yl*) (XII) (210 mg.), as small purple-black prisms, m. p. 294—297° [Found: C, 95·0; H, 4·8%; *M* (Rast), 380. $C_{46}H_{32}$ requires C, 95·6; H, 4·4%; *M*, 503]. Attempts to cyclise 1-(1-hydroxymethylene-2-indenyl)-naphthalene by other reagents met with failure. Among those tried were the following: anhydrous liquid hydrogen fluoride, hydrogen bromide in acetic acid, phosphoric oxide in benzene, and polyphosphoric acid.

Indeno[1,2,3-cd]*pyrene* (X).—*First synthesis: from indeno*[2,1-a]*perinaphthene.* A solution of maleic anhydride (30 mg.) in glacial acetic acid (7 ml.) was added to a boiling solution of indeno[2,1-*a*]perinaphthene (50 mg.) in xylene (3 ml.) and glacial acetic acid (8 ml.), and the resulting solution was boiled for 4 min. 10b : 11 : 12 : 12a-*Tetrahydroindeno*[1,2,3-cd]-*pyrene*-11 : 12-*dicarboxylic anhydride* (VIII) crystallised from the cooled solution in almost quantitative yield as colourless needles. The m. p. on a preheated block was approximately 260°. With slow heating the adduct shows no definite m. p. but becomes yellow above 230°, the colour becoming progressively darker up to 400° (Found: C, 82·8; H, 4·1. $C_{24}H_{14}O_3$ requires C, 82·2; H, 4·0%).

The adduct (20 mg.) was boiled in nitrobenzene (5 ml.) for 5 min. The cooled solution deposited *indeno*[1,2,3-cd]*pyrene*-11 : 12-*dicarboxylic anhydride* (IX) (15 mg.), which on recrystallisation from chlorobenzene–nitrobenzene (1 : 1) gave golden-yellow needles, m. p. 357—360° (Found: C, 83·0; H, 3·1. $C_{24}H_{10}O_3$ requires C, 83·2; H, 2·9%). Boiling a mixture of indeno[2,1-*a*]perinaphthene (85 mg.) and maleic anhydride (40 mg.) in nitrobenzene (4 ml.) resulted in direct formation of the fully aromatic anhydride (IX) (73 mg.) as golden-yellow needles, m. p. 358—361°.

The foregoing anhydride (73 mg.) was intimately mixed with soda-lime (4 g.) and heated strongly. *Indeno*[1,2,3-cd]*pyrene* (X) distilled off and was obtained as bright yellow plates (32 mg.), m. p. 162·5—163·5°, from light petroleum–benzene (10 : 1), after purification on a column (8 × 1·1 cm.) with light petroleum–benzene (1 : 1) as solvent and developer (Found: C, 95·9; H, 4·2. $C_{22}H_{12}$ requires C, 95·6; H, 4·4%). The hydrocarbon in solution displays a greenish-yellow fluorescence in daylight and ultraviolet light.

Second synthesis: from 1-*iodopyrene.* 1-Iodopyrene (2 g.) and *o*-bromonitrobenzene (1·55 g.) were heated at 200—205° and copper bronze (4 g.) was added gradually during 2 hr. The cooled melt was extracted exhaustively with benzene, and the extract, after concentration to low volume, was chromatographed on a column (15 × 2·5 cm.). Initial development with light petroleum–benzene (4 : 1) gave a colourless bottom zone fluorescing blue in ultraviolet light, and from which a small quantity of 1-iodopyrene was recovered. Continued development of the upper orange-yellow zone with light petroleum–benzene (1 : 1) brought through golden-yellow eluates which, after removal of solvent and trituration of the residual oil with ethyl

acetate, afforded 1-*o*-*nitrophenylpyrene* (XI) (0·875 g., 44%), as golden-yellow needles, m. p. 146·5—147·5° (Found: C, 81·7; H, 3·9; N, 4·1. $C_{22}H_{13}O_2N$ requires C, 81·7; H, 4·1; N, 4·3%).

The foregoing nitro-compound (145 mg.), suspended in glacial acetic acid (25 ml.), was reduced by hydrogen in the presence of 20% palladium–charcoal (100 mg.). Absorption ceased after 1 hr. when the theoretical volume of hydrogen had been taken up. The mixture was filtered free from catalyst and poured into water, and the resulting emulsion was extracted with ether after addition of excess of 20% sodium hydroxide solution. The ether extract was washed with water, dried, and evaporated. The residual brown oil (125 mg.) containing 1-*o*-aminophenylpyrene did not crystallise, and was characterised as its *picrate*, golden-yellow rhombohedra, m. p. 206—207·5° (from ethanol) (Found: C, 64·0; H, 3·3; N, 10·4. $C_{28}H_{18}O_7N_4$ requires C, 64·4; H, 3·5; N, 10·7%).

The crude amine (110 mg.), dissolved in glacial acetic acid (2 ml.), was added to excess of 10% sulphuric acid (3 ml.). Sodium nitrite (40 mg.) in water (1 ml.) was added all at once to the acid solution which immediately became deep red. After 3 min. an excess of urea was added, and after a further 2 min. copper bronze (1 g.) was added. The mixture was then warmed on the water-bath for 10 min. and filtered, and the residue was extracted with boiling benzene. The washed and dried (K_2CO_3) extract was evaporated to low volume and filtered through a column (8 × 2·7 cm.) with benzene–light petroleum (1 : 1) as developer. After addition of light petroleum the concentrated eluates deposited yellow plates (39 mg., 38%), m. p. 161·5—163°, which did not depress the m. p. of indeno[1,2,3-*cd*]pyrene prepared in the first synthesis and had an identical absorption spectrum. The *picrate*, prepared in benzene or alcohol, showed no definite m. p. but decomposed over the range 150—180° (Found: C, 66·3; H, 3·2; N, 8·4. $C_{22}H_{12},C_6H_3O_7N_3$ requires C, 66·5; H, 3·0; N, 8·3%).

Reactions of Indeno[2,1-a]perinaphthene with Dienophiles.—With 1 : 4-*naphthaquinone.* The hydrocarbon (110 mg.) and 1 : 4-naphthaquinone (70 mg.) in nitrobenzene (5 ml.) were boiled for 30 min. The cooled solution deposited *indeno*[1,2,3-cd]*naphtho*[2′,3′-a]*pyrene-5* : 16-*quinone* (XV) (120 mg.) which crystallised from dimethylformamide as orange needles, m. p. 263—265° (Found: C, 88·7; H, 3·5. $C_{30}H_{14}O_2$ requires C, 88·7; H, 3·5%). The quinone gives a greenish-blue vat with alkaline sodium dithionite.

With 1 : 4-*benzoquinone.* The hydrocarbon (100 mg.) and 1 : 4-benzoquinone (45 mg.) were boiled in nitrobenzene for 15 min. The microcrystalline *product* (XVIa or b) (90 mg.) separated from the boiling solution and recrystallised from nitrobenzene (50 ml.) as small orange needles, m. p. above 400° (Found: C, 90·9; H, 3·4. $C_{46}H_{20}O_2$ requires C, 91·4; H, 3·3%). It gives no vat with alkaline sodium dithionite.

Oxidation of Indeno[2,1-a]perinaphthene with Lead Tetra-acetate.—An excess of lead tetra-acetate (1·8 g.) was added to a solution of indeno[2,1-*a*]perinaphthene (200 mg.) in pure dry benzene (50 ml.) and kept at 15° for 1 hr. The solution became deep crimson and at the end of this time gave a negative test (no green coloration with 77% sulphuric acid) for indeno[2,1-*a*]-perinaphthene. It was then poured into water and worked up in the customary manner. The purple-black residue obtained after removal of solvent was passed in benzene through a column (9 × 2·7 cm.). A crimson zone passed down the column rapidly on development with benzene. The concentrated eluates from this zone yielded purple-black prisms (50 mg.), m. p. 293—296°, which did not depress the m. p. of the hydrocarbon (XII) obtained from the cyclisation of 1-(1-hydroxymethylene-2-indenyl)naphthalene and had an identical absorption spectrum (350—650 mμ). Continued washing of the column, ultimately with methanol, brought through violet eluates from which no useful product could be isolated.

Acetoxylation of Di(indeno[2,1-a]perinaphthen-12-yl).—The hydrocarbon (100 mg.) and excess of lead tetra-acetate (1 g.) in pure dry benzene (50 ml.) were boiled under reflux for 2 hr. The cooled solution was poured into water and the resulting mixture was extracted exhaustively with ether and benzene. The green extracts were washed successively with water, saturated sodium hydrogen carbonate solution, and water, and dried (Na_2SO_4). Solvent was removed under reduced pressure and the residue was purified by passage through a column (10 × 2·7 cm.) with benzene–ether (1 : 1) as eluant. The green eluates yielded 7(?)-acetoxydi(indeno-[2,1-*a*]perinaphthen-12-yl) (30 mg.) which crystallised from xylene as green needles, m. p. >360° (Found: C, 90·4; H, 4·1. $C_{42}H_{24}O_2$ requires C, 90·0; H, 4·3%).

Nitration of Indeno[2,1a]perinaphthene.—Tetranitromethane (98 mg.) in absolute ethanol (2 ml.) was added to a solution of indeno[2,1-*a*]perinaphthene (126 mg.) in pure dry pyridine (5 ml.). The initially red solution became purple-violet rapidly. It was kept at 15° for 5 min. and then diluted with ether (250 ml.). The resulting solution was washed free from pyridine and nitroform with hydrochloric acid followed by water, and was dried (Na_2SO_4) before

evaporation. The residue was filtered through a column (6 × 2·7 cm.) with pure ethyl acetate as solvent and developer. On concentration to low volume the violet eluates afforded 12(?)-*nitroindeno*[2,1-a]*perinaphthene* (22 mg.) as violet prisms, m. p. 186—190° (decomp.) (Found: C, 81·5; H, 3·5; N, 4·8. $C_{29}H_{11}O_2N$ requires C, 80·8; H, 3·7; N, 4·7%).

Oxidation of Indeno[2,1-a]*perinaphthene with Chromic Anhydride.*—Chromic anhydride (200 mg.) was added to a suspension of indeno[2,1-*a*]perinaphthene (126 mg.) in glacial acetic acid (20 ml.), and the mixture was boiled for 3 min. The solution was poured into water, and the precipitated orange solid was dissolved in chloroform. The chloroform solution was washed with aqueous sodium hydroxide and water, and dried (Na_2SO_4) before evaporation to dryness. Chromatography of the residue with chloroform–benzene as solvent and developer gave the crude *quinone* which crystallised from dimethylformamide as orange needles (52 mg.), m. p. 283—285°. After recrystallisation from dimethylformamide (twice) and then from chlorobenzene (twice) the compound had constant m. p. 290—292° (Found: C, 85·0; H, 3·7. $C_{29}H_{10}O_2$ requires C, 85·1; H, 3·6%). The quinone gives a violet-blue vat readily with alkaline sodium dithionite and a greenish-yellow colour with concentrated sulphuric acid.

The authors thank the Department of Scientific and Industrial Research for the award of a Maintenance Grant to one of them (I. M. A.), Dr. O. Kruber and colleagues for generous supplies of chemicals, and Mr. M. Zochowski for the preparation of intermediates.

Department of Chemistry, The University,
St. Andrews, Scotland. [*Received, April 10th,* 1956.]

---

676. 2-*Acyl Derivatives of Cyclic* 1 : 3-*Diones. Part III.** *Ultraviolet and Infrared Absorption Spectra of* 2-*Acylcyclohexane*-1 : 3-*diones.*

By W. R. Chan and C. H. Hassall.

The ultraviolet and infrared absorption spectra of typical 2-acyl-*cyclo*hexane-1 : 3-diones have been studied. The influences of the polarity of the solvent and variation in pH on the ultraviolet absorption spectra lead to the conclusion that these compounds are completely enolised. The infrared absorption spectra provide evidence of intramolecular conjugate chelation.

Various 2-acyl*cyclo*hexane-1 : 3-diones have been isolated from natural sources. They include calythrone,[1,2] humulone, and lupulone and related compounds,[3,4] usnic acid,[5,6] leptospermone,[7,8] angustione, and dehydroangustione,[2,9,10] and constituents of the resin of *Aspidium filix mas*.[2,11,12] Particular interest attaches to several members of the group which have activity as anthelmintics, insecticides, and antibiotics: in the last case it appears that the activity is dependent on the presence of the triketone structure in these compounds.[13]

We have studied the ultraviolet and infrared absorption spectra of 2-acyl*cyclo*hexane-1 : 3-diones to obtain knowledge of structure which may contribute to the correlation of biological activity with molecular constitution and to obtain information which may assist in the characterisation of this group of compounds.

* Part II, *J.*, 1955, 2860.

[1] Penfold and Simonsen, *J.*, 1940, 412.
[2] Birch, *J.*, 1951, 3026.
[3] Wöllmer, *Ber.*, 1925, **58**, 672.
[4] Howard and Tatchell, *J.*, 1954, 2400; *Chem. and Ind.*, 1955, 1595.
[5] Curd and Robertson, *J.*, 1937, 894.
[6] Barton, Deflorin, and Edwards, *Chem. and Ind.*, 1955, 1039.
[7] Briggs, Hassall, and Short, *J.*, 1945, 706.
[8] Briggs, Hassall, and Taylor, *J.*, 1948, 383.
[9] Cahn, Gibson, Penfold, and Simonsen, *J.*, 1931, 286.
[10] Chan and Hassall, *J.*, 1955, 2860.
[11] Boehm, *Annalen*, 1901, **318**, 230 *et seq.*
[12] McGookin, Robertson, and Simpson, *J.*, 1953, 1828.
[13] Hassall, *Experientia*, 1950, **6**, 462.

The results in Table 1 indicate that the ultraviolet absorption spectra of 2-acyl*cyclo*hexane-1 : 3-diones in ethanol have two maxima, in the region of 235 and of 275 mμ. There is variation in the relative heights of the maxima. It will be shown that this may be related to the degree of dissociation of the enolic forms of the compounds. Substitution

TABLE 1.*

	$\lambda_{max.}$ (mμ)	ε	Ref.
4 : 4 : 6 : 6-Tetramethyl-2-*iso*valeryl*cyclo*hexane-1 : 3 : 5-trione (I)	238, 279	7900, 11,600	
2-Acetyl-4 : 4 : 6 : 6-tetramethyl*cyclo*hexane-1 : 3 : 5-trione (II) ...	235, 277	8450, 10,500	
2-Acetyl-5 : 5-dimethyl*cyclo*hexane-1 : 3-dione (III)	231, 277	10,000, 10,000	2
2-Acetyl*cyclo*hexane-1 : 3-dione (IV)	235, 275	14,700, 11,600	14
2-Acetyl-4 : 4 : 6-trimethyl*cyclo*hexane-1 : 3-dione (VI)	233, 276	13,500, 13,500	10
2-Acetyl-4 : 4 : 6-trimethyl*cyclo*hex-5-ene-1 : 3-dione (VII)	233, 279	9000, 6200	
Usnic acid	233, 285	22,300, 22,800	
Flavaspidic acid	229, 292·5	26,350, 20,300	15
Albaspidin	223, 271	27,300, 13,400	15
Humulone	237, 282	13,760, 8330	16
Lupulone	228, 280	14,080, 6210	16

* Compounds dissolved in ethanol.

at the 4- or the 6-position in the *cyclo*hexane ring leads to minor variations in $\lambda_{max.}$ values. There are similar maxima (223—233 and 271—293 mμ) in the spectra of acyltetronic acids [17] and compounds containing an acylphloroglucinol nucleus.[18]

The molecular extinction values at the two maxima of the model compound 4 : 4 : 6 : 6-tetramethyl-2-*iso*valeryl*cyclo*hexane-1 : 3 : 5-trione (I) vary with concentration (Table 2).

TABLE 2.

Solvent	Concn. (10^{-5} M)	$\lambda_{max.}$ (mμ)	ε
4 : 4 : 6 : 6-*Tetramethyl*-2-iso*valeryl*cyclo*hexane*-1 : 3 : 5-*trione*			
95% EtOH	10	238, 279	7520, 11,530
,, ...	5	238, 279	7300, 11,800
,, ...	4	238, 279	6920, 12,400
,, ...	3	238, 279	6500, 13,000
,, ...	2	238, 279	5750, 14,000
,, ...	1	238, 276	4700, 14,500
EtOH–HCl	10	238, 279	8300, 10,800
*cyclo*Hexane	10	234, 281	8900, 10,720
2-*Acetyl*-5 : 5-*dimethyl*cyclo*hexane*-1 : 3-*diones*			
95% EtOH	10	231, 277	10,000, 10,000
EtOH–HCl	10	232, 276	10,000, 9700
*cyclo*Hexane	10	230, 276	10,160, 9800

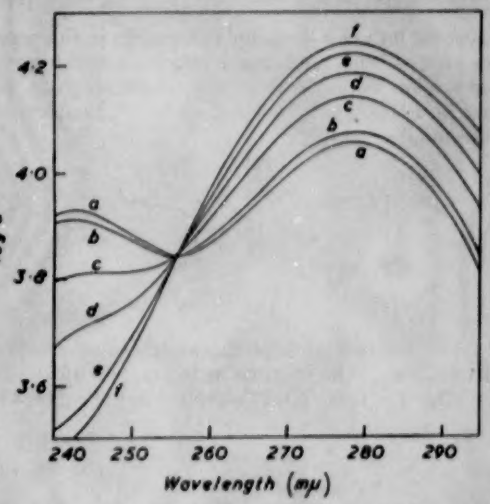
With increasing dilution the height of the maximum at 238 mμ decreases while that at 279 mμ increases. Also, the compounds (I) and (II) in *cyclo*hexane absorb more strongly in the 230 mμ region but less in the 279 mμ region than when solutions in ethanol are involved.

The ultraviolet absorption spectra of 2-acyl*cyclo*hexane-1 : 3-diones are sensitive to changes in pH. The results for the ketone (I), which are typical, are shown in the Figure. The single sharp isosbestic point (λ 256 mμ, log ε 3·84) indicates that only two molecular species are involved in the change in pH. It is evident that these are the enol and the corresponding ion, the latter being responsible for the maximum at 279 mμ. The results in Table 2 are in agreement with this. The increase in the proportion of ion with increasing dilution in an ionising solvent is the expected behaviour of a relatively weak acid.

[14] Smith, *J.*, 1953, 803.
[15] Mulholland, Thesis, Manchester, 1947.
[16] Cook and Harris, *J.*, 1950, 1873.
[17] Lacey, *J.*, 1954, 832.
[18] Birch and Todd, *J.*, 1952, 3102.

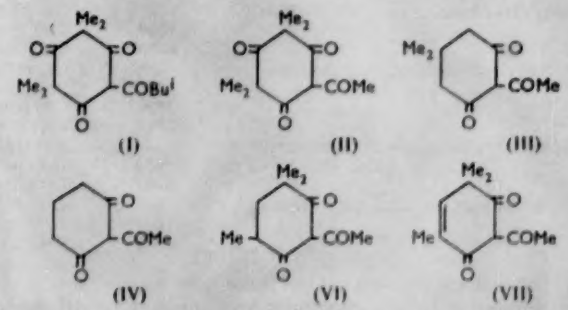
Keto-enol equilibria are very sensitive to change in the polarity of solvent. In non-polar solvents, compounds such as Meldrum's acid, *cyclo*hexane-1 : 3-dione, and *cyclo*hexane-*spiro*-5-*cyclo*hexane-1 : 3-dione are largely in the keto-form, but the typical 2-acyl*cyclo*-hexanone, benzoylcamphor, is 95% enolised. In polar solvents the *cyclo*hexane-1 : 3-diones are largely enolic and benzoylcamphor mainly (58%) in the keto-form.[19] The close similarity of the molecular extinction values of the 2-acyl*cyclo*-1 : 3-diones (I) and (III) in ethanol–hydrochloric acid and in *cyclo*hexane indicates that enolisation is essentially complete in both solvents.

There are two ways of interpreting the variation in the form of the absorption spectrum with change in pH. Either the maxima at 238 and 279 mμ are separately due to the undissociated enol and the corresponding ion respectively, or the absorption at pH 1·2



Ultraviolet-light absorption of 4 : 4 : 6 : 6-*tetramethyl*-2-*isovaleryl*cyclo*hexane*-1 : 3 : 5-*trione at* pH (*a*) 1·22, (*b*) 3·38, (*c*) 4·31, (*d*) 4·73, (*e*) 5·41, (*f*) 13.

(and in *cyclo*hexane) is due to the enol alone, *i.e.*, the enol has maxima at both 238 and 279 mμ while the ion has a maximum at 279 mμ alone. We favour the second alternative.



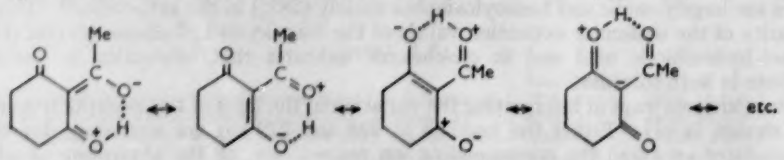
To accept the first would imply that in *cyclo*hexane or in 0·1N-hydrochloric acid the compound (I) is substantially ionised. This is unreasonable as it is a relatively weak acid, having pK_a estimated by potentiometric titration * as 5·0.

In considering the ultraviolet absorption spectrum of 2-acetyl*cyclo*hexane-1 : 3-dione,

* The potentiometric titration was carried out in 20% ethanol. The pK_a value deduced from the absorption spectra by plotting pH against ε (at $\lambda_{max.}$), separately for the enol and the enol ion, is 4·5. The difference between the two values is doubtless due, at least in part, to the use of different solvents.

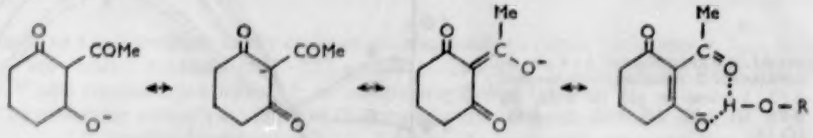
[19] Eistert and Reiss, *Chem. Ber.*, 1954, **87**, 92.

Smith [14] suggested that the maximum at 235 mμ (ε 14,700) arises from the αβ-unsaturated carbonyl system in the enol formulated as (IVa) while the maximum at 275 mμ (ε 11,600) may be attributed to the conjugated diene chromophore in the ring involving hydrogen bonding. There is no evidence that such a compact, cross-conjugated system may be



(IVa) (IVb) (IVc) (IVd)

dissected into two chromophoric groups in this way. In fact it seems preferable to regard the enol as being a resonance hybrid of such forms as (IVa—d). The corresponding forms for the ion would be (Va—d). There are good indications from the studies on 2-acetyl-*cyclo*hexanone that "solvent chelate" complexes such as (Vd) may exist in hydroxylic solvents.[19]



(Va) (Vb) (Vc) (Vd)

The infrared absorption spectra of several 2-acyl*cyclo*hexane-1 : 3-diones have been determined. The maxima in the regions 1900—1400 and 4000—2700 cm.$^{-1}$ are recorded in Table 3. There is no absorption in the region 3520—3100 cm.$^{-1}$, where simple hydrogen-

TABLE 3.

Compound	Liquid film (cm.$^{-1}$)	$CHCl_3$–1% EtOH (cm.$^{-1}$)	Assignment
4 : 4 : 6 : 6-Tetramethyl-2-*iso*valeryl*cyclo*hexane-1 : 3 : 5-trione (I)	2650—2450	—	OH (H-bonded)
		1715	C=O (unconjugated)
		1660	C=O (conjugated)
		1550	C=O (conjugate chelate)
2-Acetyl-5 : 5-dimethyl*cyclo*hexane-1 : 3-dione (III)	2700—2500	—	OH (H-bonded)
		1656	C=O (conjugated)
		1555	C=O (conjugate chelate)
2-Acetyl-4 : 4 : 6-trimethyl*cyclo*hex-5-ene-1 : 3-dione	2700—2440	—	OH (H-bonded)
		1660	C=O (conjugated)
		1630	C=C (conjugated)
		1540	C=O (conjugate chelate)
2-Acetyl-4 : 4 : 6-trimethyl*cyclo*hexane-1 : 3-dione	2630—2410	—	OH (H-bonded)
		1650	C=O (conjugated)
		1543	C=O (conjugated chelate)
2-Acetyl*cyclo*hexane-1 : 3-dione [14]	2630 (diffuse)	—	OH (H-bonded)
		1680	C=O (conjugated)
		1565	C=O (conjugated chelate)

bonded hydroxyl bands normally appear, but there is an indication of a very broad band of low intensity and without a definite maximum overlapping the C–H stretching frequencies near 2800 cm.$^{-1}$ and extending to approximately 2500 cm.$^{-1}$. In all cases there are strong bands in the region 1678—1650 cm.$^{-1}$. These fall close to the range 1685—1665 cm.$^{-1}$ assigned to αβ-unsaturated ketones and may reasonably be attributed to conjugated carbonyl groups. The absence of carbonyl absorption in the region 1725—1705 cm.$^{-1}$, except in the case of the ketone (I) which has an isolated carbonyl group, indicates that the 2-acyl*cyclo*hexane-1 : 3-diones are completely enolised.

All the spectra have a very intense band at 1565—1540 cm.$^{-1}$. There are several recorded examples of carbonyl absorption in this region. Enolised acetylacetone and

dibenzoylmethane do not absorb in the usual αβ-unsaturated ketone region but have very strong bands [20] between 1639 and 1538 cm.$^{-1}$. 2-Hydroxyacetophenone and salicylaldehyde have bands at 1639—1613 cm.$^{-1}$ and the examination of a series of aromatic ketones has shown that the *o*-hydroxyl group is necessary for the shift of the carbonyl band from its normal position.[21,22] Cyclic β-keto-esters,[23] tetronic acids,[24] *cyclo*hexane-1 : 3-diones,[20,25] and chelated hydroxy-quinones [26,27] have bands between 1656 and 1538 cm.$^{-1}$. In all these cases the position of this absorption maximum has been attributed to conjugate chelation [20]—the formation of unusually strong hydrogen bonds through the stabilisation arising from ionic resonance forms. The strong bands at 1565—1540 cm.$^{-1}$ in the spectra of 1-acyl*cyclo*hexane-1 : 3-diones may be explained in terms of conjugate-chelation effects. Ionic resonance forms such as (IVb) will make an important contribution to the stabilisation of hydrogen bonds. The effect is enhanced by the symmetry of the β-triketone system. The bands are not dependent on concentration. It follows that no significant proportion of an intermolecular hydrogen-bonded form is present. The broad hydroxyl band (2700—2410 cm.$^{-1}$) of low intensity is a consequence of the conjugate chelation.[20]

Bellamy [25] has correlated the frequency of the conjugated chelate carbonyl band in aliphatic β-diketones such as acetylacetone and aromatic aldehydes, or in ketones such as 2 : 4-dihydroxybenzaldehyde and 1 : 5-dihydroxyanthraquinone, with the double-bond character of the enol or ring double bond. He has shown that there is a linear relation such that for complete double-bond character the carbonyl frequency for this class of compound is 1600 cm.$^{-1}$. The carbonyl shift due to conjugate chelation in 2-acyl*cyclo*hexane-1 : 3-diones is greater than this. No doubt this is due to the effect of conjugation with the second carbonyl group in the *cyclo*hexane ring. It is significant that the band (1678—1650 cm.$^{-1}$) due to this carbonyl group is at a somewhat lower frequency than that normally found for αβ-unsaturated ketones.

The information obtained from the ultraviolet and infrared absorption spectra is in agreement. It leads to the conclusion that 2-acyl*cyclo*hexane-1 : 3-diones should be regarded as completely enolised, with unusually strong intramolecular hydrogen bonds.

Experimental

2-Acyl*cyclo*hexanediones were freshly purified and distilled. Stock solutions for spectroscopic measurements were made up in 95% ethanol which had been purified by distillation from sodium hydroxide and silver oxide. Ultraviolet-absorption measurements were made with a Beckman spectrophotometer, model DU, with the same matched pair of 1 cm. quartz cells throughout. Measurements summarised in the Figure were carried out in approx. 0·1N-sodium hydroxide, 0·1N-sulphuric acid, and phosphate–citric acid buffer solutions. Aliquot parts of the stock solution were diluted with appropriate volumes of the buffer solutions. Measurements of pH were made with a Cambridge meter.

The pK_a values were determined by potentiometric titration of the compound (approx. 10^{-3}M in 20% ethanol–water) against 0·1N-barium hydroxide. The pK_a value was read in the usual way from the graph of pH against volume of alkali used.

Infrared absorption spectra were determined on Perkin–Elmer double-beam spectrometers (model 21B), for each compound at several concentrations in chloroform and as a liquid film. We are indebted to Dr. L. J. Bellamy and Dr. Seymour Bernstein for these determinations.

One of us (W. R. C.) acknowledges with thanks the award of a Geddes-Grant Fellowship and a grant from Messrs. Roche Products Ltd.

Chemistry Department,
University College of the West Indies, Jamaica. [*Received, April 23rd,* 1956.]

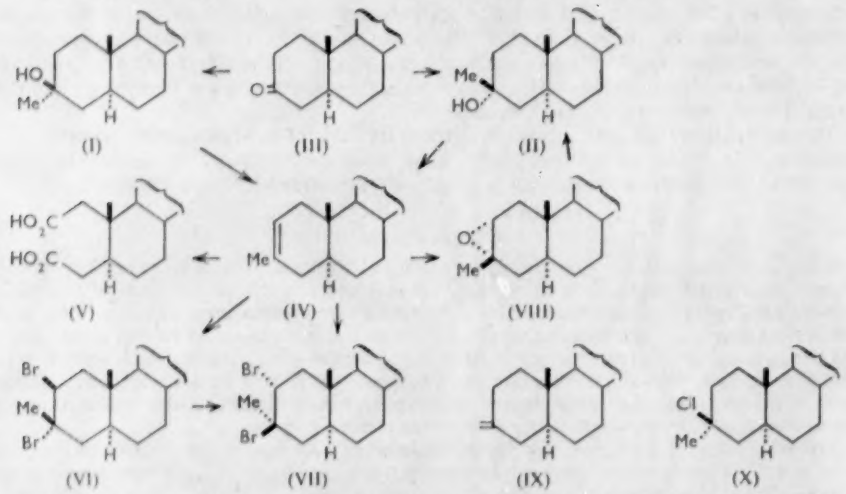
[20] Rasmussen, Tunnicliff, and Brattain, *J. Amer. Chem. Soc.*, 1949, **71**, 1068.
[21] Gordy, *J. Chem. Phys.*, 1940, **8**, 516.
[22] Hunsberger, *J. Amer. Chem. Soc.*, 1950, **72**, 5626.
[23] Leonard, Gutowsky, Middleton, and Peterson, *J. Amer. Chem. Soc.*, 1952, **74**, 4070.
[24] Duncanson, *J.*, 1953, 1207.
[25] Bellamy, *J.*, 1954, 4487.
[26] Flett, *J.*, 1948, 1441.
[27] Hadži and Sheppard, *Trans. Faraday Soc.*, 1954, **50**, 911.

677. *The 3-Methylcholestanols and their Derivatives.*

By D. H. R. Barton, A. da S. Campos-Neves, and R. C. Cookson.

Configurations have been assigned to the two 3-methylcholestanols. 3-Methylcholest-2-ene and 3-methylenecholestane have been prepared and characterised. All four compounds afford in high yield the same 3β-chloro-3α-methylcholestane on treatment with hydrogen chloride. The process is regarded as kinetically rather than thermodynamically controlled. Corresponding experiments with hydrogen bromide afford 3β-bromo-3α-methylcholestane. Reduction of these two halides with lithium and liquid ammonia affords, after protonation, 3β-methylcholestane. Some of the results presented have already been summarised in preliminary form.[1]

Stereochemical aspects of carbonium-ion behaviour in alicyclic systems have not been the subject of extensive investigation. *tert.*-Carbonium ions are, of course, most easily generated and are best suited for study. In aliphatic systems *tert.*-carbonium ions show only weak stereochemical preference [2,3] with a slight excess of inversion over racemisation. The present investigation was initiated in order to determine the stereochemical fate of a *tert.*-carbonium ion generated from a tertiary alcohol, or from the appropriate olefin, in a conformationally unambiguous alicyclic system. The results obtained led us to investigate several other aspects of conformational behaviour in the system chosen.



Two epimeric tertiary alcohols, (I) and (II), were easily obtained [4,5,6] from cholestanone (III) and the methyl Grignard reagent. Both alcohols, which were characterised as their *p*-nitrobenzoates, readily lost water on treatment with acetic acid containing a trace of perchloric acid, to give the known anhydro-derivative.[4,5,6,7] This was proved to be 3-methylcholest-2-ene (IV), for on successive oxidations with osmium tetroxide, lead tetra-acetate, and sodium hypobromite it furnished *seco*cholestane-2 : 3-dioic acid [8] (V).

3-Methylcholest-2-ene was further characterised by addition of bromine, the major

[1] Barton, *Experientia*, 1955, Suppl. II, p. 121; see also Barnes and Palmer, *Austral. J. Chem.*, 1956, **9**, 105.
[2] Doering and Zeiss, *J. Amer. Chem. Soc.*, 1953, **75**, 4733, and references there cited.
[3] Hughes, Ingold, Martin, and Meigh, *Nature*, 1950, **166**, 679.
[4] Farmer and Kon, *J.*, 1937, 414.
[5] Bolt and Backer, *Rec. Trav. chim.*, 1937, **56**, 1139.
[6] Kuwada and Miyasaka, *J. Pharm. Soc. Japan*, 1938, **58**, 115; *Chem. Abs.*, 1938, **32**, 7474.
[7] Kon and Woolman, *J.*, 1939, 794.
[8] Windaus and Uibrig, *Ber.*, 1914, **47**, 2384.

product being 2β : 3α-dibromo-3β-methylcholestane (VI) and the minor the 2α : 3β-isomer (VII). The configurations are based on the principle of preferred diaxial addition [9] and on the relative rotations {$[\alpha]_D$ +89° for (VI), and −15° for (VII)} as compared with the rotations of 2β : 3α- and 2α : 3β-dibromocholestane [9] ($[\alpha]_D$ +76° and −29° respectively). In agreement with the assigned configurations [9] the 2β : 3α-dibromide (VI) rearranged to the more stable 2α : 3β-isomer (VII) in boiling chloroform solution; also [9] the diaxial compound (VI) was more easily eluted from alumina than the diequatorial isomer (VII). In agreement with the assigned stereochemistry [10] the diaxial isomer (VI) showed infrared bands (in carbon disulphide) at 537 and 547 cm.$^{-1}$ and the diequatorial compound bands at 752 and 804 cm.$^{-1}$.

Configurations were assigned to the two tertiary alcohols (I) and (II) on the following evidence. First, both showed carbon–oxygen stretching frequencies at 940 and 893 cm.$^{-1}$ (in carbon disulphide) in agreement [11] with the presence of equatorial and axial hydroxyl groups respectively. Secondly, treatment of 3-methylcholest-2-ene (IV) with perphthalic acid gave an epoxide which was reduced by lithium aluminium hydride to the alcohol (II). The diaxial epoxide opening rule requires that the hydroxyl group formed by the reduction be axial, that is α-oriented as in (II). The oxide must, therefore, have the α-configuration (VIII) as would be expected.

The behaviour of the two tertiary alcohols (I) and (II) on dehydration with phosphorus oxychloride in pyridine was also in agreement with the assigned configurations. The α-alcohol (II) afforded the olefin (IV) in high yield. The β-alcohol (I), on the other hand, gave an isomeric olefin mixture recognised as substantially (IX) by its infrared spectrum [maxima at 883 (strong) and 1647 cm.$^{-1}$ (medium) in Nujol], by its conversion by osmium tetroxide followed by lead tetra-acetate into cholestanone, and by comparison with the pure compound (IX) obtained from this ketone by the Wittig reaction.[12] The olefin (IX) was further characterised by conversion into two dibromides neither of which was identical with the two dibromides obtained from 3-methylcholest-2-ene (IV). The major dibromide from 3-methylenecholestane has been tentatively formulated as the 3α(axial)-bromide on the basis of preferred diaxial addition [9] and because it was much less stable thermally than its equatorial isomer.

The α-alcohol (II), with the axial hydroxyl group, has four centres coplanar (2β-H, $C_{(2)}$, $C_{(3)}$, and 3α-OH) for elimination towards $C_{(2)}$. The β-alcohol, with the equatorial hydroxyl group, does not, of course, satisfy this geometric requirement. Adequate coplanarity is, however, readily obtained with the aid of a suitable 3-methyl hydrogen atom, thus provoking elimination to give the exocyclic methylene isomer (IX).

Treatment of either of the tertiary alcohols (I) and (II), or of 3-methylcholest-2-ene (IV) or 3-methylenecholestane (IX), with hydrogen chloride in dioxan at room temperature gave in approximately 75% isolated yield the same chloride, m. p. 154—156°, $[\alpha]_D$ +33°. The total yield of the chloride was determined by an isotope dilution method to be 82%. The chloride was identified as 3β-chloro-3α-methylcholestane (X) on the basis of the following evidence. First, the compound showed an infrared frequency (carbon disulphide solution) at 782 cm.$^{-1}$ corresponding [10] to an equatorial (β) bond. Secondly, treatment with collidine gave a product identified by its dibromide as the olefin (IX). The identity was confirmed by stepwise oxidation (see above) to cholestanone. The direction of elimination is consonant with equatorial (β) chlorine, not axial (α) chlorine.

We regard the chloride (X) as the more stable epimer because 1-methyl*cyclo*hexyl chloride, where the molecule is free to adopt either conformation for the carbon–chlorine bond, shows only the frequency at 772 cm.$^{-1}$ (carbon disulphide solution) characteristic [10] of equatorial chlorine. In all four carbonium-ion reactions the more stable epimer is, therefore, the major product. The same result is obtained in the addition of hydrogen chloride to cholest-5-ene, the product being 5α-chlorocholestane.[13] Such a conclusion

[9] Alt and Barton, *J.*, 1954, 4284.
[10] Barton, Page, and Shoppee, *J.*, 1956, 331.
[11] Page, *J.*, 1955, 2017, and references there cited.
[12] Wittig and Schollkopf, *Chem. Ber.*, 1954, **87**, 1318.
[13] Bernal, Crowfoot, and Fankuchen, *Phil. Trans.*, 1940, *A*, **239**, 135; Crowfoot in "Vitamins and Hormones," Vol. II, p. 409, Academic Press, New York, 1944.

would, of course, be self-evident if the reactions were reversible and thus subject to thermodynamic control. At least for the chloride (X) this does not seem probable, for the extent of solvolysis of the chloride in 90% aqueous dioxan at 20° was insignificant even after seven days. In contrast the approximate times of half-reaction for the formation of the chloride (X) were as follows : from the α-alcohol (II), 30 min. ; from the β-alcohol (I), 4 hr. ; from the olefin (IV), 13 min. Since the forward reaction is so fast and the back-reaction under comparable conditions so slow, we reject the idea of thermodynamic control and conclude that the formation of the more stable configuration is indeed a rate-controlled process. There remains the problem of whether the chloride (X) is formed directly from the carbonium ion or through the olefin (IV) after elimination of water. We hope to present a detailed account of this aspect of the problem on a subsequent occasion.

It is of interest to compare the stereospecificity of addition of bromine or chlorine to the ethylenic linkage with that of hydrogen chloride, all additions being of the ionic type. Diaxial addition of halogen is well established [9] and, at least for the case of the 5 : 6-ethylenic linkage of cholesterol and its congeners, the initial halgenonium ion is formed on the less hindered α-side of the molecule, the process of addition being completed non-Markownikoff-wise.[14] It is clear that the addition of hydrogen chloride to 3-methylcholest-2-ene and to cholest-5-ene cannot be of analogous stereochemical form.

Some of the experiments summarised above for hydrogen chloride have been repeated with hydrogen bromide. Thus the tertiary alcohols (I) and (II) and the olefin (IV) gave the same bromide in 75% isolated yield. The bromide is formulated as 3β-bromo-3α-methylcholestane on the basis of its infrared frequency at 780 cm.$^{-1}$ (in carbon disulphide) corresponding to equatorial bromine.[10] * Again one must note the predominant formation of the more stable product.

From some recent comments on the behaviour of carbanions [15,16] one can conclude that the steric requirements of a carbon–carbon bond, a carbanion, and a carbon–hydrogen bond are in that diminishing order. If this is correct then reduction of 3β-chloro- or 3β-bromo-3α-methylcholestane by lithium in liquid ammonia should afford,[15,16] on protonation, 3β-methylcholestane for the steric requirements of CMe should be greater than those of the carbanion. This conclusion was confirmed by experiment although the 3β-methylcholestane obtained had somewhat different properties from those recorded [6,17] in the literature. An authentic specimen was therefore prepared from methyl cholestane-3β-carboxylate [18,19] by reduction with lithium aluminium hydride to 3β-hydroxymethylcholestane, conversion into the toluene-*p*-sulphonate, and further reduction with the same reagent.[20] 3β-Methylcholestane was also obtained by hydrogenation of 3-methylcholest-2-ene (IV).

Experimental

Rotations were taken in $CHCl_3$ solution. Infrared spectra were kindly determined by Dr. J. E. Page of Messrs. Glaxo Laboratories Ltd., and by Dr. G. Eglinton using, unless stated to the contrary, carbon disulphide as solvent. The light petroleum used was of b. p. 40—60°.

3-*Methylcholestan*-3α- *and* -3β-*ol*.—Cholestanone, m. p. 128—129°, $[\alpha]_D$ +39° (*c* 1·21), (5·2 g.) in dry ether (50 ml.) was added to methylmagnesium iodide [prepared from methyl iodide (4·8 g.) and magnesium (1·02 g.) in dry ether (18 ml.)] with good stirring during 30 min. and the resulting solution refluxed for 2 hr. The product, in 3 : 2 light petroleum–benzene (50 ml.), was chromatographed over neutralised alumina (75 g.) (27 fractions). Elution with the same

* Some of the infrared bands shown to be characteristic [10] for equatorial and axial chlorine and bromine may correspond to polarised or coupled C–H deformation modes rather than to carbon–halogen stretching frequencies. Such a change in the assumed origin of these bands would not, of course, influence the purely empirical correlation [10] with the conformation of the halogen. We thank Dr. G. Eglinton for this helpful comment.

[14] Fieser, *Experientia*, 1950, **6**, 312; Barton, Miller, and Young, *J.*, 1951, 2598.
[15] Barton and Robinson, *J.*, 1954, 3045.
[16] Roberts and Shoppee, *J.*, 1954, 3418.
[17] Baker, Minckler, and Petersen, *J. Amer. Chem. Soc.*, 1955, **77**, 3644.
[18] Corey and Sneen, *ibid.*, 1953, **75**, 6234.
[19] Roberts, Shoppee, and Stephenson, *J.*, 1954, 2705.
[20] Schmid and Karrer, *Helv. Chim. Acta*, 1949, **32**, 1371.

solvent mixture, with benzene and with 9 : 1 benzene–ether (19 fractions in all) gave 3β-methylcholestan-3α-ol (2·90 g.), m. p. (from ethyl acetate–methanol) 126—127°, $[\alpha]_D$ +28° (*c* 1·68). Elution with 1 : 1 benzene–ether and with ether alone (8 fractions in all) afforded 3α-methylcholestan-3β-ol (2·19 g.), m. p. (from acetic acid) 147—149°, $[\alpha]_D$ +34° (*c* 1·24). Kuwada and Miyasaka [6] reported m. p. 125° and 147—148° respectively.

The two alcohols were characterised as follows. The alcohol (1·0 g.) in dry ether (50 ml.) was stirred for 1 hr. with a solution of phenyl-lithium prepared from bromobenzene (782 mg.) and excess of lithium wire in dry ether (150 ml.) with stirring for 2 hr. *p*-Nitrobenzoyl chloride (2·0 g.) in dry ether (25 ml.) was added and the solution left overnight. Crystallisation of the product from ethyl acetate–methanol afforded *3β-methylcholestan-3α-yl* p-*nitrobenzoate*, needles, m. p. 159—160°, $[\alpha]_D$ +20° (*c* 1·03) (Found: C, 76·45; H, 9·45. $C_{35}H_{53}O_4N$ requires C, 76·2; H, 9·7%). The derivative from the β-alcohol was only obtained crystalline with difficulty (gel) by chromatography over neutralised alumina (45 g.) in benzene. Crystallisation from acetic acid gave *3α-methylcholestan-3β-yl* p-*nitrobenzoate*, needles, m. p. 194°, $[\alpha]_D$ +30° (*c* 1·75) (Found: C, 76·3; H, 9·7%).

3-Methylcholest-2-ene.—The two stereoisomeric alcohols behaved in the same way on treatment with acetic acid–perchloric acid. The alcohol (40 mg.) in " AnalaR " acetic acid (2 ml.) with addition of perchloric acid (70%; two drops) was heated on the steam-bath for 30 min. The product was filtered through alumina in light petroleum and crystallised from the same solvent, then having m. p. 82—83°, $[\alpha]_D$ +74° (*c* 1·32), +74° (*c* 1·39). The olefin can be conveniently prepared by the same treatment of the mixed alcohols from the Grignard reaction on cholestanone.

3-Methylcholest-2-ene (233 mg.) in dry dioxan (10 ml.) was treated with osmium tetroxide (210 mg.) in the same solvent (10 ml.) and left at room temperature in the dark for 3 days. The osmate was cleaved by saturation with hydrogen sulphide and, after filtration, the dioxan was removed *in vacuo*. The residue was taken up in " AnalaR " acetic acid (30 ml.) with addition of lead tetra-acetate (740 mg.) in the same solvent (20 ml.) and left for one day (uptake 1·0 mol. of tetra-acetate). The product in dry dioxan (20 ml.) was treated with sodium hypobromite solution (2·0 ml.) [prepared by adding bromine (2 ml.) to ice-cold water (26·5 ml.) containing sodium hydroxide (6·3 g.)], and the solution stirred for 5 hr. at room temperature. The acidic fraction of the product was crystallised from ether–light petroleum, to give *seco*cholestane-2 : 3-dioic acid (34 mg.), identified by m. p., mixed m. p. and rotation {$[\alpha]_D$ +35° (*c* 0·85)}. The authentic specimen, prepared by chromic acid oxidation of cholestanol according to Windaus and Uibrig,[8] had m. p. 196—198°, $[\alpha]_D$ +35° (*c* 0·95).

3-Methylcholest-2-ene (412 mg.) in carbon tetrachloride (20 ml.) was titrated with bromine (15% w/w; in carbon tetrachloride). Removal of the solvent *in vacuo* at room temperature and chromatography over alumina in light petroleum (development with the same solvent) gave two dibromides. Eluted more easily was 2β : 3α-*dibromo*-3β-*methylcholestane* (440 mg.), needles (from ethyl acetate–methanol), m. p. 106—108° (decomp.), $[\alpha]_D$ +89° (*c* 1·23) (Found: C, 62·25; H, 8·65; Br, 29·15. $C_{28}H_{48}Br_2$ requires C, 61·75; H, 8·9; Br, 29·35%). Eluted with more difficulty was 2α : 3β-*dibromo*-3α-*methylcholestane*, m. p. (from ethyl acetate–methanol) 160—162°, $[\alpha]_D$ −15° (*c* 0·82) (Found: C, 61·7; H, 9·05; Br, 29·4%). The 2β : 3α-dibromide (220 mg.) in chloroform (35 ml.) was refluxed for 97 hr. (no further change in rotation). Removal of the chloroform *in vacuo* and crystallisation from ethyl acetate–methanol gave the 2α : 3β-dibromide, identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ −16° (*c* 1·03)}.

2α : 3α-Epoxy-3β-methylcholestane.—3-Methylcholest-2-ene (500 mg.) was treated with 3 mols. of perphthalic acid in ether overnight at room temperature (uptake of 1 mol.). Filtration of the product in light petroleum over silica gel gave *2α : 3α-epoxy-3β-methylcholestane*, m. p. (from alcohol) 133—135°, $[\alpha]_D$ +47° (*c* 1·17) (Found: C, 83·85; H, 11·65. $C_{28}H_{48}O$ requires C, 83·95; H, 12·1%). This epoxide (1·4 g.) in ether (100 ml.) was reduced with an excess of lithium aluminium hydride (2·8 g.) in the same solvent (100 ml.) under reflux for 40 hr. Crystallisation from ethanol gave 3β-methylcholestan-3α-ol, identified by m. p. and mixed m. p.

3-Methylenecholestane (IX).—Triphenylmethylphosphonium bromide [13] (2·77 g.) was treated with phenyl-lithium (651 mg.) in dry ether (46 ml.) with shaking for 3 hr. To this solution there was added cholestanone (3·0 g.), and the solution was refluxed overnight. After being washed with water, the ethereal solution was dried (Na_2SO_4) and evaporated *in vacuo*. The residue was refluxed with excess of lithium aluminium hydride in ether. After being worked up in the usual way the product was filtered in light petroleum through alumina (50 g.). Elution with the same solvent (150 ml.) afforded *3-methylenecholestane* (1·6 g.), needles (from ethyl acetate–methanol), m. p. 65—66°, $[\alpha]_D$ +23° (*c* 2·16 in CCl_4) (Found: C, 87·7; H, 12·45. $C_{28}H_{48}$

requires C, 87·4; H, 12·6%). This hydrocarbon (89·5 mg.) in carbon tetrachloride (10 ml.) containing one drop of " AnalaR " pyridine was titrated with bromine (3·36% w/v) in the same solvent. After removal of the solvent *in vacuo* at room temperature the oily product was chromatographed over silica gel (2·0 g.) in light petroleum (5 ml.). Elution with the same solvent (30 ml.) gave 3α-*bromo*-3β-*bromomethylcholestane* (91·7 mg.), flat needles (from ethyl acetate), m. p. 116—118°, $[\alpha]_D$ +38° (*c* 1·65) (Found: C, 62·25; H, 8·8; Br, 29·45. $C_{28}H_{46}Br_2$ requires C, 61·75; H, 8·9; Br, 29·35%). Further elution with the same solvent (15 ml. and 45 ml.) gave respectively a mixture (16·8 mg.) and then 3β-*bromo*-3α-*bromomethylcholestane* (16·6 mg.), needles (from ethyl acetate), m. p. 124—126°, $[\alpha]_D$ +23° (*c* 1·14) (Found: C, 61·35; H, 9·05; Br, 29·6%). The two dibromides gave a marked depression in m. p. on admixture.

Conversion of 3-*Methylenecholestane into Cholestanone.*—3-Methylenecholestane (162 mg.) in dry dioxan (5 ml.) was treated with osmium tetroxide (139 mg.) in the same solvent (5 ml.) at room temperature for 48 hr. The osmium tetroxide complex was cleaved with hydrogen sulphide,[21] and the product crystallised from ethanol, to furnish the *glycol*, blades, m. p. 208—209°, $[\alpha]_D$ +29° (*c* 0·71) (Found: C, 79·85; H, 12·45. $C_{28}H_{50}O_2$ requires C, 80·3; H, 12·1%). In an identical experiment the total glycol in ethanol (10 ml.) and dioxan (35 ml.) was treated with periodic acid (308 mg.) in water (5 ml.) for 16 hr. (uptake of 1 mol. of oxidant). After being worked up in the usual way the product was filtered in benzene through alumina (3 g.). Elution with the same solvent gave cholestanone (130 mg., 80%), identified by m. p., mixed m. p., and rotation.

3β-*Methylcholestane.*—(a) *From cholestane*-3β-*carboxylic acid.* Methyl cholestane-3β-carboxylate [18, 19] (1·2 g.) in dry ether (50 ml.) was reduced with a large excess of lithium aluminium hydride in the same solvent under reflux for 6 hr. Crystallisation of the product from ethyl acetate–methanol gave 3β-*hydroxymethylcholestane*, needles, m. p. 151—152°, $[\alpha]_D$ +28° (*c* 1·28) (Found: C, 83·65; H, 12·35. $C_{28}H_{50}O$ requires C, 83·5; H, 12·5%). This alcohol (1·1 g.) in dry pyridine (30 ml.) was treated with toluene-*p*-sulphonyl chloride (3·0 g.) in the same solvent (20 ml.) overnight at room temperature, to furnish the *toluene*-p-*sulphonate*, m. p. (from chloroform–methanol) 113—114°, $[\alpha]_D$ +22° (*c* 1·02) (Found: C, 74·65; H, 9·9. $C_{35}H_{56}O_3S,\frac{1}{4}CH_4O$ requires C, 74·4; H, 10·2%). This toluene-*p*-sulphonate (496 mg.) in ether (50 ml.) was reduced with a large excess of lithium aluminium hydride under reflux for 72 hr. to 3β-methylcholestane (350 mg.), m. p. (from chloroform–methanol) 105—106°, $[\alpha]_D$ +28° (*c* 1·76). For this compound Baker, Minckler, and Petersen [17] reported m. p. 97—98°, $[\alpha]_D$ +11°.

(b) *From* 3-*methylcholest*-2-*ene.* The olefin (223 mg.) in 1 : 1 ethyl acetate–acetic acid (60 ml.) was hydrogenated over platinum, to give 3β-methylcholestane (200 mg.), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +27° (*c* 1·23)}.

(c) *From* 3β-*chloro*-3α-*methylcholestane.* The chloro-compound (see below) (140 mg.) in dry ether (30 ml.) was added during 10 min. to a solution of lithium (150 mg.) in liquid ammonia at −60° and the solution stirred for 5 hr. Excess of ammonium chloride was added and ammonia left to evaporate. Crystallisation from chloroform–methanol gave 3β-methylcholestane (100 mg.), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +28° (*c* 0·84)}. In a second experiment 3β-chloro-3α-methylcholestane (102 mg.) in 1 : 1 ether–acetic acid (60 ml.) was treated with excess of zinc dust during 18 hr. at room temperature (good stirring). Chromatography of the product over silica gel (3·0 g.) in light petroleum gave 3β-methylcholestane (26 mg.), identified by m. p., mixed m. p., rotation {$[\alpha]_D$ +28° (*c*, 0·89)}, and negative Beilstein test, as well as unchanged starting material (66 mg.), identified by m. p., mixed m. p., and positive Beilstein test.

(d) *From* 3β-*bromo*-3α-*methylcholestane.* The bromo-compound (see below) (97·7 mg.) in dry ether (20 ml.) was slowly (10 min.) dropped with stirring into a solution of lithium (101 mg.) in liquid ammonia (25 ml.) and left with stirring for 2 hr. Protonation with ammonium chloride and working up in the usual way gave a crystalline residue (76·3 mg.). One crystallisation from ethyl acetate–methanol gave 3β-methylcholestane (61 mg.), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +27° (*c* 1·12)}.

Dehydration of the 3-*Methylcholestanols.*—3β-Methylcholestan-3α-ol (see above) (240 mg.) in dry pyridine (25 ml.) and redistilled phosphorus oxychloride (290 ml.) was left for 24 hr. at room temperature. Crystallisation of the product from chloroform–methanol afforded 3-methylcholest-2-ene (200 mg.), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +70° (*c* 1·29)}.

The same dehydration procedure was applied to 3α-methylcholestan-3β-ol. The resulting

[21] Barton and Elad, *J.*, 1956, 2085.

olefin (194 mg.) was chromatographed over silica gel (50 g.) in light petroleum. All fractions melted indefinitely between 56° and 63° and had rotations close to 40°. A typical mixture had m. p. (from ethyl acetate–methanol) 57—59°, $[\alpha]_D$ +44° (*c* 0·85) (Found: C, 87·1; H, 12·25. Calc. for $C_{28}H_{48}$: C, 87·4; H, 12·6%). In order to characterise the olefin mixture the following experiments were performed. The mixture (1·4 g.) in carbon tetrachloride (25 ml.) was titrated with bromine (15% w/v) in the same solvent. The resulting mixture of dibromides was chromatographed over silica gel in light petroleum, elution being with the same solvent. The first eluted dibromide (1·2 g.), plates (from ethyl acetate–methanol), had m. p. 114° (decomp.), $[\alpha]_D$ +44° (*c* 1·12), and was identified (m. p. and mixed m. p.) as 3α-bromo-3β-bromomethylcholestane. The second eluted dibromide (260 mg.) formed needles (from ethyl acetate–methanol), m. p. 124—126° (decomp.), $[\alpha]_D$ +23° (*c* 1·14), and was identified (m. p. and mixed m. p.) as 3β-bromo-3α-bromomethylcholestane.

The olefin mixture (400 mg.) in dry dioxan was treated with osmium tetroxide (400 mg.) in the same solvent (5 ml.) and left in the dark at room temperature for 2 days. After saturation with hydrogen sulphide and filtration, the dioxan was removed *in vacuo* and the residue in "AnalaR" acetic acid (25 ml.) was oxidised with lead tetra-acetate (1·0 g.) in the same solvent (25 ml.) at room temperature for 4 hr. (1 mol. uptake). The product (360 mg.) was chromatographed over neutralised alumina (8 g.) in light petroleum. Elution with 1 : 4 benzene–light petroleum gave cholestanone (192 mg., pure), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +40° (*c*, 1·20)}.

3β-*Chloro-3α-methylcholestane.*—3-Methylcholest-2-ene (265 mg.), 3-methylenecholestane (250 mg.), 3β-methylcholestan-3α-ol (210 mg.), and 3α-methylcholestan-3β-ol (245 mg.) were treated separately with dry hydrogen chloride in dioxan (23% w/v; 25 ml.) for 8 days at room temperature and then for 3 days at 0°. All four solutions deposited pure 3β-*chloro-3α-methylcholestane*, m. p. 154—156°, unchanged on crystallisation from light petroleum, $[\alpha]_D$ +32° (*c* 0·92), +33° (*c* 1·02), +33° (*c* 0·93), and +33° (*c* 1·05) respectively (Found: C, 79·9; H, 11·6. $C_{28}H_{49}Cl$ requires C, 79·85; H, 11·7%). Concentration of the mother-liquors *in vacuo* at room temperature gave further crops of the chloride, the total yields being 76, 70, 76, and 70% respectively. The experiments were repeated, the mixtures being left for 24 hr. only at room temperature, with the same results.

In order to determine the total yield of chloride in the above experiments an isotope dilution method was employed. 3-Methylcholest-2-ene was converted into the chloride as above but with deuterium chloride instead of hydrogen chloride. The ordinary chloride has a strong infrared band (carbon disulphide solution) at 783 cm.$^{-1}$ whereas the deuterated material shows no absorption at this frequency. It is simple, therefore, to analyse mixtures of the two substances. 3-Methylcholest-2-ene (90·0 mg.) and the deuterated 3β-chloro-3α-methylcholestane (10·95 mg.) were treated with hydrogen chloride in dioxan as above. The first crop of chloride, m. p. 154—156°, $[\alpha]_D$ +33° (*c* 1·05), was shown to contain 12·0% of labelled chloride. The true yield of 3β-chloro-derivative from the 3-methylcholest-2-ene is, therefore, 82%. The method of analysis is, of course, only valid provided that there is no exchange between ordinary chloride and deuterated chloride. This was checked in two ways: (*a*) the ordinary chloride was treated with deuterium chloride in dioxan, and (*b*) the deuterated chloride was treated with hydrogen chloride in the same solvent. Infrared examination of the product (see above) showed that in each case there was no exchange.

In order to determine the approximate times of half-reaction the following experiments were carried out. 3-Methylcholest-2-ene (92 mg.) in hydrogen chloride–dioxan (23% w/v; 25 ml.) was kept at room temperature (20°) and the reaction followed polarimetrically. The initial rotation was +75° (8 min. after dissolution) {cf. $[\alpha]_D$ for 3-methylcholest-2-ene: +80° (*c* 0·88 in dioxan)}. After 120 min. the rotation was constant at 37°. The time of half-reaction was 14 min. 3β-Methylcholestan-3α-ol (108 mg.) was treated in the same way for 30 min. The product was chromatographed over silica gel (5 g.) in light petroleum. Elution with this solvent gave 3-methylcholest-2-ene (2·2 mg.), identified by m. p., mixed m. p., and negative Beilstein test. Further elution with the same solvent furnished the chloride (60 mg., 53%), identified by m. p., mixed m. p., and positive Beilstein test. Elution with benzene afforded unchanged starting material (48 mg.). 3α-Methylcholestan-3β-ol (103 mg.), treated in the same way for 2 hr., gave 3-methylcholest-2-ene (8 mg.), the chloride (29 mg., 27%), and unchanged alcohol (68 mg.).

3β-Chloro-3α-methylcholestane (100 mg.) in dioxan (65 ml.) and water (5 ml.) was left for 7 days at 20°. The solvent was removed *in vacuo* at room temperature to give back starting material (100 mg.) unchanged (m. p., mixed m. p., and positive Beilstein test).

Treatment of 3β-Chloro-3α-methylcholestane with Collidine.—The chloride (171 mg.) in dry redistilled collidine (5 ml.) was heated under reflux for 3 hr. The product was treated with osmium tetroxide and then with lead tetra-acetate, as described for the processing of the dehydration product of 3α-methylcholestan-3β-ol, to give cholestanone (57 mg.), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +40° (*c*, 1·23)}. In a second experiment the chloride (34 mg.), treated as above with collidine, furnished a product which on titration with bromine gave 3α-bromo-3β-bromomethylcholestane (30 mg.), identified by m. p., mixed m. p., and rotation {$[\alpha]_D$ +44° (*c* 0·75)}. This dibromide was worked up as before (see above).

3β-Bromo-3α-methylcholestane.—3-Methylcholest-2-ene (203 mg.), 3β-methylcholestan-3α-ol (200 mg.), and 3α-methylcholestan-3β-ol (203 mg.) were treated separately with dry hydrogen bromide in dioxan (25% w/v; 25 ml.) at room temperature (20°) for 7 days. In each case *3β-bromo-3α-methylcholestane* crystallised in pure condition (76, 73, and 74% respectively). It had m. p. 138—139°, unchanged on recrystallisation from cold dry light petroleum, $[\alpha]_D$ +35° (*c* 1·09) (Found: C, 72·1; H, 10·35; Br, 16·8. $C_{27}H_{49}Br$ requires C, 72·25; H, 10·6; Br, 17·15%). The infrared spectra of all three preparations were identical.

We thank the Government Grants Committee of the Royal Society, the Central Research Fund of London University, and Imperial Chemical Industries Limited for financial assistance and Messrs. Glaxo Laboratories Limited for generous gifts of chemicals. One of us (A. da S. C.-N.) is indebted to the Instituto de Alta Cultura (Portugal) for a Research Scholarship.

Birkbeck College, London, W.C.1.
The University, Glasgow, W.2.

[*Received, April 25th*, 1956.]

---

678. *The Mechanisms of Inhibition and Retardation in Radical Polymerizations. Part III.* The Use of a Stable Free Radical as an Inhibitor.*

By J. C. Bevington and N. A. Ghanem.

A stable free radical can be prepared by oxidation of a condensation product of acetone and phenylhydroxylamine. This radical is an inhibitor for the polymerization of styrene and of methyl α-methylacrylate. The induction periods are well defined, and the inhibitor is converted into products which do not affect the rate of polymerization; in these respects the radical is an ideal inhibitor, but the stoicheiometry of the reactions occurring during the induction periods is uncertain and therefore this inhibitor cannot be used for measuring rates of initiation in radical-chain reactions.

Banfield and Kenyon [1] showed that reaction of acetone with phenylhydroxylamine gave a crystalline product, *N*-(3-*N*-hydroxyanilino-1 : 3-dimethylbutylidene)aniline oxide (I). This material was oxidized by silver oxide to a red crystalline product (II), the free-radical nature of which was confirmed by physical measurements.[2,3,4] This radical appears to be stable at 0° but at room temperature in a period of a few weeks it becomes discoloured and loses its crystalline form. In this paper the effects of this radical on sensitized polymerizations and on the decomposition of αα′-azo*iso*butyronitrile are described.

(I) $Me_2C(Ph{\cdot}N{\cdot}OH)-CH_2-C(=O{\leftarrow}N{\cdot}Ph)Me$ $\quad$ $Me_2C(Ph{\cdot}N{\cdot}O\cdot)-CH_2-C(=O{\leftarrow}N{\cdot}R)Me$ $\quad$ (II): R = Ph $\quad$ (III): R = *p*-C_6H_4Me

Diphenylpicrylhydrazyl has been used as an inhibitor of polymerizations [5] and to measure the rate of generation of radicals from typical initiators of polymerization.[6] There

* Part II, Bevington, Ghanem, and Melville, *J.*, 1955, 2822.

[1] Banfield and Kenyon, *J.*, 1926, 1612.
[2] Holden, Kittel, Merritt, and Yager, *Phys. Rev.*, 1950, **77**, 147.
[3] Van den Handel, *Physica*, 1952, **18**, 921.
[4] Chu, Pake, Paul, Townsend, and Weissman, *J. Phys. Chem.*, 1953, **57**, 504.
[5] Bartlett and Kwart, *J. Amer. Chem. Soc.*, 1952, **74**, 3969.
[6] Bawn and Mellish, *Trans. Faraday Soc.*, 1951, **47**, 1216.

is evidence that one hydrazyl radical reacts with one radical but the mechanism of this reaction is uncertain.[7] There are other objections to the use of the hydrazyl in quantitative work; first, the products of the scavenging reaction can themselves react with free radicals and, secondly, it seems that the scavenger fails to react with all the radicals which are generated in solution by the dissociation of azo*iso*butyronitrile.[7] Radical (II) is less stable and presumably more reactive than diphenylpicrylhydrazyl, and also it does not contain nitro-groups which may be responsible for the reactivity of the products formed from the hydrazyl. For these reasons it was decided to examine the possibility of using the radical (II) as a radical scavenger.

The polymerizations at 60° of styrene and methyl α-methylacrylate sensitized by azo*iso*butyronitrile were studied, in presence of the radical (II) in various concentrations. The decomposition at 60° of the initiator in the presence of the radical (II) in benzene solution was also studied by using the ^{14}C-azo-compound so that products of the direct interaction of 2-cyano-2-propyl radicals could be determined by isotope dilution analysis.

FIG. 1. *Conversion–time plots showing the inhibitory effect of the radical* (II) *on the sensitized polymerization of styrene.* (*Numbers on curve are expt. nos.*)

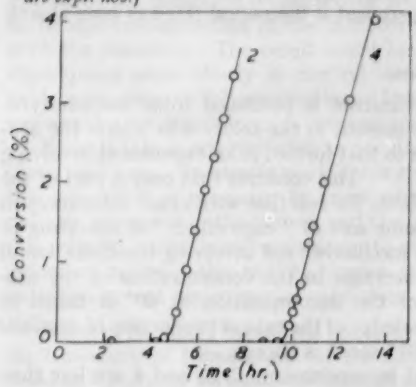
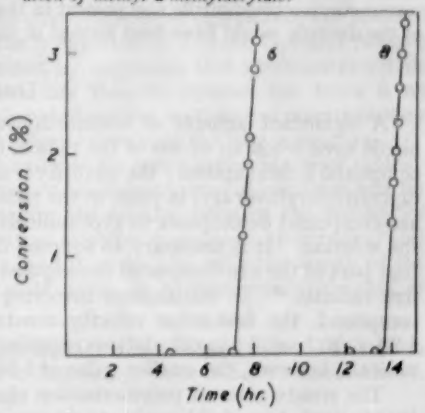


FIG. 2. *Conversion–time plots showing the inhibitory effect of* (II) *on the sensitized polymerization of methyl α-methylacrylate.*



EXPERIMENTAL

Materials and Methods.—The substances (I) and (II) were prepared by the methods of Banfield and Kenyon.[1] The preparations and purifications of the other substances and the experimental procedures have been described previously.[8,9]

An attempt was made to prepare the radical (III) from acetone and *p*-tolylhydroxylamine. The first product corresponding to the oxide (I) was isolated; oxidation of this product with silver oxide gave a red solution in light petroleum but a crystalline product could not be isolated.

Results.—Polymerizations of styrene in bulk at 60° in the complete absence of air were performed, with azo[^{14}C]*iso*butyronitrile at a concentration of 0·300 g./l. and various concentrations of the radical (II); typical conversion–time plots are shown in Fig. 1. The radical caused a well-defined induction period during which the colour disappeared completely; afterwards the rate rapidly attained a steady value. The induction periods were recorded as the intercepts on the time axis of the linear portions of the conversion–time plots. The polymers recovered from these experiments by precipitation in methanol showed no sign of coloration. Polymers were assayed after reprecipitation; the rates of initiation of polymerization were calculated from the specific activities of the polymers and the initiator, and the overall rates of polymerization. The results of these experiments are summarized in Table 1.

Similar experiments were performed with methyl α-methylacrylate in place of styrene, with initiator at a concentration near 0·200 g./l.; these experiments are referred to in Fig. 2 and

[7] Bevington, *J.*, 1956, 1127.
[8] Bevington, Melville, and Taylor, *J. Polymer Sci.*, 1954, **12**, 449.
[9] Bevington, *J.*, 1954, 3707.

Table 2. The radical (II) introduced induction periods, followed by reactions at steady rates. The recovered polymers were white.

TABLE 1.

Expt. no.	Concn. of (II) (g./l.)	Induction period (min.)	Steady rate of polymn. (%/hr.)	Rate of initiation (10^{-6} mole $l.^{-1}$ $sec.^{-1}$)
1	0	0	1·37	2·26
2	0·199	290	1·29	2·11
3	0·355	464	1·20	2·06
4	0·509	585	1·11	1·71

TABLE 2.

Expt. no.	5	6	7	8
Concn. of (II) (g./l.)	0	0·102	0·198	0·206
Induction period (min.)	0	440	720	815
Steady rate of polymn. (%/hr.)	4·63	3·86	3·32	3·95

An air-free solution of azo[^{14}C]*iso*butyronitrile (2·83 mg.) and radical (II) (10·0 mg.) in benzene (2·15 c.c.) was kept at 60° for 16 hr. Subsequent analysis showed that 0·20 mg. of tetramethylsuccinodinitrile was present in the solution. From previous work,[9] about 0·48 mg. of the dinitrile would have been formed in this experiment if the radical (II) had been absent.

DISCUSSION

A significant amount of tetramethylsuccinodinitrile is produced from azo*iso*butyronitrile even when an excess of the radical (II) is present in the solution in which the azo-compound is decomposed; the quantity is similar to that formed in an experiment involving diphenylpicrylhydrazyl in place of the radical (II).[7] This confirms that only a part of the azo-compound decomposes to give radicals available for reaction with other substances in the solution. It is necessary to suppose that some sort of " cage effect " is operating or that part of the azo-compound decomposes by a mechanism not involving the liberation of free radicals.[10] In calculations involving the decrease in the concentration of the azo-compound, the first-order velocity constant for the decomposition at 60° is taken as $1·20 \times 10^{-5}$ $sec.^{-1}$; in calculations requiring knowledge of the rate of production of *available* radicals, however, the smaller value of $1·00 \times 10^{-5}$ $sec.^{-1}$ is chosen.

The steady rates of polymerization observed in experiments 2, 3, and 4 are less than that in expt. 1, probably owing to decomposition of initiator during the induction periods. The observed rates of polymerization can be corrected to those for an initiator concentration of 0·300 g./l. by assuming that the rate is proportional to (initiator concentration)$^{\frac{1}{2}}$ and that the velocity constant for the decomposition of the initiator is $1·20 \times 10^{-5}$ $sec.^{-1}$. The corrected rates for expts. 2, 3, and 4 are respectively 1·43, 1·42, and 1·35%/hr.; these rates are quite close to that for expt. 1. It is concluded that products formed during the induction period are not retarders. The rates of initiation quoted in Table 1 are not corrected for decomposition of the initiator; if this correction is made, the rates of initiation for a concentration of initiator of 0·300 g./l. are 2·26, 2·59, 2·86, and $2·53 \times 10^{-6}$ mole $l.^{-1}$ $sec.^{-1}$ for experiments 1, 2, 3, and 4 respectively. These figures suggest that products formed from the radical (II) during the induction period do not significantly interfere in the initiation of polymerization.

The corrected rates of polymerization for methyl α-methylacrylate at an initiator concentration of 0·200 g./l. are 4·63, 4·56, 4·37 and 5·27%/hr. for experiments 5, 6, 7, and 8 respectively. The agreement between these rates is not as good as that in the polymerizations involving styrene, but there is no evidence that retarders are formed during the induction period.

One of the objections to the use of diphenylpicrylhydrazyl as a radical scavenger is that products formed from it are reactive. In this respect, radical (II) is much superior to the hydrazyl.

The number of radicals generated from the initiator during the induction period can be

[10] Hammond, Sen, and Boozer, *J. Amer. Chem. Soc.*, 1955, **77**, 3244.

calculated and then compared with the number of inhibitor radicals consumed. It is assumed that the inhibitor is completely used during the induction period. The results of the calculations are summarized in Table 3; 1 l. of reaction mixture is considered, and numbers of radicals are expressed in moles.

TABLE 3.

Expt. no.	2	3	4	6	7	8
No. of radicals generated (r) $\times 10^4$	5·7	8·9	10·7	5·5	8·3	9·6
No. of inhibitor radicals consumed (i) $\times 10^4$	6·7	12·0	17·1	3·4	6·7	6·9
i/r	1·18	1·35	1·60	0·62	0·81	0·72

For the experiments involving styrene, *viz.*, nos. 2, 3, and 4, the ratio i/r is considerably greater than 1. This indicates either that more than one inhibitor radical is needed to react with a 2-cyano-2-propyl radical, or that at 60° the inhibitor is gradually consumed by a reaction not involving the radicals generated from the initiator. The latter explanation seems the more likely since radical (II) is slightly unstable even at room temperature; further, it accounts for the fact that i/r increases with the length of the induction period. The results for styrene are at variance with those for methyl α-methylacrylate for which the ratio i/r is less than 1. This result is unexpected since the nature of the monomer should not affect the induction period during which the only reactions of significance are believed to be the decomposition of the initiator and the interaction of 2-cyano-2-propyl radicals with the inhibitor. The result could be explained by supposing that azo*iso*butyronitrile decomposes more slowly in methyl α-methylacrylate than in styrene, but there is no evidence to support this assumption. It is concluded that there is at present no satisfactory explanation for the difference between the experiments involving the two monomers.

Radical (II) is not regarded as an inhibitor suitable for quantitative study of radical-chain reactions. In kinetic work, inhibitors are used to evaluate rates of initiation and for this purpose it is necessary to know with certainty the relation between the number of radicals generated in the system and the quantity of inhibitor consumed. For radical (II) this relation varies from one system to another, and it varies also with the length of the induction period; the radical cannot therefore be used for measurements of rates of initiation except under special conditions.

One of us (N. A. G.) thanks the University of Alexandria for an extension to study leave, and the University of Birmingham for the award of a Fellowship. We thank Professor H. W. Melville, F.R.S., for his continued interest and help.

THE CHEMISTRY DEPARTMENT, THE UNIVERSITY,
BIRMINGHAM, 15.

[*Received, April 26th*, 1956.]

---

679. *Sulphanilamide Derivatives: Compounds derived from 2- and 4-Aminoquinazoline and 1-Aminophthalazine.*

By H. J. RODDA.

The preparation and properties of 2- and 4-aminoquinazoline have been re-investigated and 1-aminophthalazine has been prepared. These compounds have been converted into their sulphanilyl derivatives.

IN a preliminary note published some time ago [1] the preparation of 2- and 4-amino- and 2- and 4-sulphanilamido-quinazoline was reported and later 1-amino- and 1-sulphanilamido-phthalazine were prepared. Discrepancies between the results obtained in this work and other attempts to prepare some of these compounds make it desirable to record details.

Dewar [2] prepared 2-aminoquinazoline by amination of 2-chloroquinazoline in alcohol, having obtained very poor yields of the base by the condensation of *o*-aminobenzaldehyde and guanidine carbonate or cyanamide. It has now been found that refluxing guanidine carbonate and pure *o*-aminobenzaldehyde in a high-boiling solvent (*e.g.*, decalin) gives

[1] Macbeth and Rodda, *Nature*, 1945, **156**, 207.
[2] Dewar, *J.*, 1944, 619.

almost theoretical yields of 2-aminoquinazoline. The product with *p*-nitrobenzenesulphonyl chloride in anhydrous pyridine readily gives 2-*p*-nitrobenzenesulphonamidoquinazoline, which is reduced by iron powder and hydrochloric acid to 2-sulphanilamidoquinazoline.

There are several references to the preparation of 4-aminoquinazoline but there is some disagreement about its properties. Dewar [2] obtained a product, m. p. 250—260°, which is described as being practically non-basic and incapable of acylation. In the same manner Tomisek and Christensen [3] prepared a compound, designated also as 4-aminoquinazoline, m. p. 245—260°, which formed an acetyl derivative, m. p. 172°, with some difficulty. More recently, Morley and Simpson [4] prepared 4-aminoquinazoline by amination of the 4-chloro-compound with ammonia, or with ammonium carbonate in phenol, and by reaction of 4-phenoxyquinazoline with ammonium acetate. In each case, the product, m. p. 267° (decomp.), had pronounced basic properties and was readily acetylated, yielding 4-acetamidoquinazoline, m. p. 174—175°. Notwithstanding the evidence presented by the last authors, and confirmed subsequently by determination of pK_a values,[5] Naff and Christensen [6] reported that 4-aminoquinazoline has amide-like characteristics, thus confirming Dewar's [2] observations. In our hands alcoholic ammonia and 4-chloroquinazoline gave a basic product, m. p. 272—273°, crystallising readily from water. This material reacted readily with acid chlorides. Our results, therefore, agree with those of Morley and Simpson.[4]

Reaction of 4-aminoquinazoline with *p*-nitrobenzenesulphonyl chloride in anhydrous pyridine gave, normally, 4-*p*-nitrobenzenesulphonamidoquinazoline which is readily reduced (iron powder–hydrochloric acid) to 4-sulphanilamidoquinazoline.

1-Chlorophthalazine [7] with hot methanolic ammonia under pressure, smoothly gives 1-aminophthalazine hydrochloride. The free amino-compound, liberated by alkali, is a strong base which reacts readily with acyl halides, and forms crystalline salts with inorganic acids, including nitric acid. 1-Sulphanilamidophthalazine has been prepared in the usual manner *via* 1-*p*-nitrobenzenesulphonamido- or 1-*p*-acetamidobenzenesulphonamido-phthalazine.

Experimental

4-Aminoquinazoline.—4-Chloroquinazoline [8] aminated by a procedure similar to that described by Dewar [2] gave a product, m. p. 269—270°. Pure 4-aminoquinazoline, m. p. 272—273°, was obtained by repeated crystallisation from water (Found: C, 66·1; H, 4·8. Calc. for $C_8H_7N_3$: C, 66·2; H, 4·9%). 4-Acetamidoquinazoline crystallised from light petroleum (b. p. 100—120°) as fine white needles, m. p. 171° (Morley and Simpson [4] give m. p. 174—175°) (Found: C, 64·3; H, 4·7. Calc. for $C_{10}H_9ON_3$: C, 64·1; H, 4·9%). *4-Aminoquinazoline picrate*, crystallised from alcohol, had m. p. 292° (Found: C, 45·2; H, 2·8. $C_{10}H_{14}O_7N_6$ requires C, 44·9; H, 2·7%).

4-*p*-*Nitrobenzenesulphonamidoquinazoline.*—Recrystallised *p*-nitrobenzenesulphonyl chloride (9·2 g.) was added slowly to a cold (0°), stirred solution of 4-aminoquinazoline (6 g.) in anhydrous pyridine (40 c.c.). The mixture was heated at 60° for 1 hr., then poured with stirring into cold water (400 c.c.), and the stirring continued for several hours. The moist solid was extracted with 2% aqueous ammonia (400 c.c.) for 30 min. Acidification (hydrochloric acid) of the extract gave 4-*p*-nitrobenzenesulphonamidoquinazoline as a buff solid of satisfactory purity for subsequent reduction. Purification was difficult, repeated crystallisation from 50% aqueous alcohol giving the compound as pale yellow plates, m. p. 214—219° and for which analyses were not very satisfactory (Found, *e.g.*: C, 49·4; H, 3·0. Calc. for $C_{14}H_{10}O_4N_4S$: C, 50·9; H, 3·1%).

4-Sulphanilamidoquinazoline.—Reduced iron powder (4 g.) was added slowly to a warm (60°) stirred suspension of 4-*p*-nitrobenzenesulphonamidoquinazoline in water (120 c.c.), ethanol (40 c.c.), and concentrated hydrochloric acid (1·6 c.c.). The temperature was then raised to 75° and kept thereat for 30 min. The end of the reduction was indicated by the development

[2] Tomisek and Christensen, *J. Amer. Chem. Soc.*, 1945, **67**, 2112.
[4] Morley and Simpson, *J.*, 1949, 1354.
[5] Keneford, Morley, Simpson, and Wright, *J.*, 1949, 1356.
[6] Naff and Christensen, *J. Amer. Chem. Soc.*, 1951, **73**, 1372.
[7] Gabriel and Neumann, *Ber.*, 1893, **26**, 523.
[8] Bogert, *J. Amer. Chem. Soc.*, 1909, **31**, 509.

of a chocolate-brown colour. 10% Sodium hydroxide solution (12 c.c.) was added and the alkaline solution filtered, acidified with hydrochloric acid, treated with charcoal, made alkaline with ammonia, treated again with charcoal, and neutralised. 4-*Sulphanilamidoquinazoline* (2·4 g.) was precipitated as a cream-coloured powder, m. p. 253—255°. A sample crystallised from 50% aqueous alcohol for analysis had m. p. 255° (Found: C, 56·2; H, 3·9. $C_{14}H_{12}O_2N_4S$ requires C, 56·0; H, 4·0%).

2-*Aminoquinazoline*.—(a) *From* o-*aminobenzaldehyde*. Pure *o*-aminobenzaldehyde (12 g.) was thoroughly ground with guanidine nitrate (19 g.) and sodium carbonate (8 g.), suspended in dry decalin (200 c.c.), and stirred under reflux with stirring and removal of water, while heated successively at 180° (10 min.), 220°, 180°, the total heating time being 30 min. The hot decalin solution was decanted through a filter and cooled; crude 2-aminoquinazoline was deposited. A second extraction of the residual solids yielded a further quantity (total yield 13·6 g.; m. p. 194—200°). Precipitation with ammonia from a solution in 10% hydrochloric acid, followed by vacuum-sublimation, yielded 2-aminoquinazoline, m. p. 203—204° (Dewar[3] gives m. p. 198°) (Found: C, 66·2; H, 4·9. Calc. for $C_8H_7N_3$: C, 66·2; H, 4·9%).

(b) *From* 2-*chloroquinazoline*. 2-Chloroquinazoline (2 g.) was heated with 25% aqueous ammonia (75 c.c.) at 250° for 2 hr. The cooled mixture deposited 2-aminoquinazoline as yellow crystals (10 g.), m. p. 198°. Purified by sublimation the product had m. p. 203—204° undepressed by a sample prepared from *o*-aminobenzaldehyde.

2-Acetamidoquinazoline crystallised from acetone as long needles, m. p. 177° (Found: C, 63·9; H, 4·7. Calc. for $C_{10}H_9ON_3$: C, 64·1; H, 4·9%). 2-Aminoquinazoline picrate formed needles (from acetone), m. p. 253° (Found: C, 44·8; H, 2·6. $C_{14}H_{10}O_7N_6$ requires C, 44·9; H, 2·7%).

2-*Aminoquinazoline* p-*nitrobenzenesulphonate*, crystallised from 50% ethanol, had m. p. 249—250° (Found: C, 48·5; H, 3·6. $C_{14}H_{13}O_5N_4S$ requires C, 48·3; H, 3·5%).

2-p-*Nitrobenzenesulphonamidoquinazoline*.—*p*-Nitrobenzenesulphonyl chloride (4·4 g.) was added slowly to a stirred solution of 2-aminoquinazoline (3 g.) in anhydrous pyridine (10 c.c.); the mixture was heated on a water-bath for 1 hr., then poured into cold water (100 c.c.). The oil which separated slowly solidified and was washed to remove pyridine. The brown amorphous product (5·5 g.), although impure, was suitable for reduction. Purification was effected by extracting the crude solid with 2% sodium hydroxide solution (3 × 50 c.c.). Acidification (pH 6·5) of the extract gave 2-p-*nitrobenzenesulphonamidoquinazoline* as a pale yellow powder, m. p. 234—238°. From acetone–light petroleum (1 : 1) the compound crystallised as fine cream-coloured needles but the melting point was not improved (Found: C, 50·9; H, 3·2. $C_{14}H_{10}O_4N_4S$ requires C, 50·9; H, 3·1%).

2-*Sulphanilamidoquinazoline*.—Crude 2-*p*-nitrobenzenesulphonamidoquinazoline (5·6 g.) was stirred vigorously in a mixture of water (90 c.c.), ethanol (30 c.c.), and concentrated hydrochloric acid (3 c.c.) at 65° and reduced iron powder (3 g.) was added during 10 min. The temperature was raised to 75° for a further 35 min. during which the mixture changed from dark-grey to reddish-brown. The mixture was cooled to 50° before 50% sodium hydroxide solution (25 c.c.) was added. The insoluble material was removed and the filtrate made acid with hydrochloric acid; most of the solid, initially precipitated, redissolved, leaving a red gelatinous material in suspension. This was removed by filtration (Supercel) and the clarified filtrate neutralised with ammonia. The precipitated cream-coloured, gelatinous solid became granular at 0° overnight. Crystallisation from 50% ethanol gave 2-*sulphanilamidoquinazoline* as feathery white crystals, m. p. 286° (Found: C, 56·1; H, 4·0. $C_{14}H_{12}O_2N_4S$ requires C, 56·0; H, 4·0%).

1-*Aminophthalazine*.—1-Chlorophthalazine (30 g.) was heated at 160° for 8 hr. with methanolic ammonia (300 c.c., *ca.* 10N). The alcoholic solution was then evaporated under reduced pressure and the pale brown residue of hydrochloride was extracted with boiling water (200 c.c.). The aqueous solution was taken to dryness, finally in a vacuum desiccator over sulphuric acid. The solid was extracted with absolute alcohol and the extract again taken to dryness. Slightly more than the theoretical quantity of sodium hydroxide dissolved in the minimum of hot alcohol was added to the residue, and the mixture heated to boiling and filtered from sodium chloride. Evaporation of the alcoholic solution gave the amine slightly contaminated with sodium chloride. Crystallisation from water gave 1-*aminophthalazine* (17 g.) as cream-coloured needles, m. p. 210—211°. A sample was further purified by sublimation at 190°/0·5 mm. and then had m. p. 211° (Found: C, 66·4; H, 4·8. $C_8H_7N_3$ requires C, 66·2; H, 4·9%).

1-*Aminophthalazine hydrochloride*, crystallised from *iso*pentyl alcohol or aqueous dioxan, had m. p. 205—206° (Found: C, 52·6; H, 4·4. $C_8H_8N_3Cl$ requires C, 52·9; H, 4·4%). The

nitrate recrystallised from 10% nitric acid as long, flat needles, m. p. 220° (decomp.) (Found: C, 46·1; H, 3·7. $C_8H_8O_3N_4$ requires C, 46·1; H, 3·9%), the *picrate* as yellow needles (from water), m. p. 301° (Found: C, 45·1; H, 2·6. $C_{14}H_{10}O_7N_6$ requires C, 44·9; H, 2·7%), and the *p-nitrobenzenesulphonate* (from water) had m. p. 226° (Found: C, 48·8; H, 3·5. $C_{14}H_{12}O_5N_4S$ requires C, 48·3; H, 3·5%).

1-*Acetamidophthalazine*, prepared by use of acetic anhydride–glacial acetic acid and precipitated therefrom by light petroleum, crystallised from acetone as needles, m. p. 185° (Found: C, 64·1; H, 4·7. $C_{10}H_9ON_3$ requires C, 64·1; H, 4·9%).

1-*Benzamidophthalazine* crystallised from 40% aqueous pyridine as yellow prisms, m. p. 146° (Found: C, 72·2; H, 4·2. $C_{15}H_{11}ON_3$ requires C, 72·3; H, 4·5%).

1-p-*Nitrobenzenesulphonamidophthalazine.*—*p*-Nitrobenzenesulphonyl chloride (11 g.) was added to a stirred suspension of 1-aminophthalazine (7·2 g.) in anhydrous pyridine (20 c.c.) at 0°. The mixture was heated to 80° in 30 min. The dark brown solution was poured, with vigorous stirring, into ice-water (100 c.c.) and after several hours the precipitated solid was removed and washed with water to remove pyridine. The solid, after drying, was extracted with boiling acetone, the required product being relatively insoluble. The residue of 1-*p*-nitrobenzenesulphonamidophthalazine (6 g.) was a yellow, crystalline powder, m. p. 223—225°. This was suitable for reduction. Crystallisation from a large volume of acetone followed by sublimation at 175°/0·05 mm. gave a material, m. p. 229—230°, but analyses were unsatisfactory (Found: C, 49·4; H, 3·0. Calc. for $C_{14}H_{10}O_4N_4S$: C, 50·9; H, 3·1%).

1-*Sulphanilamidophthalazine.*—(a) *From the nitro-compound.* 1-*p*-Nitrobenzenesulphonamidophthalazine (3·2 g.) in aqueous-ethanolic hydrochloric acid was reduced with iron as described above. The 1-*sulphanilamidophthalazine*, crystallised from alcohol (1 g. in 500 c.c.), had m. p. 242° (Found: C, 56·1; H, 3·9. $C_{14}H_{12}O_2N_4S$ requires C, 56·0; H, 4·0%).

(b) Via 1-p-*acetamidobenzenesulphonamidophthalazine.* 1-Aminophthalazine (1·4 g.), suspended in anhydrous pyridine (10 c.c.), was treated with *p*-acetamidobenzenesulphonyl chloride (2·3 g.), heated on a water-bath for 1 hr., cooled, and poured into ice-water (100 c.c.). The viscous oil, which separated, solidified at 0° in several hours. The crude sulphonamide was extracted with 1% sodium hydroxide solution (100 c.c.), and the clarified extract made acid (Congo-red) with hydrochloric acid. The precipitated 1-*p*-acetamidobenzenesulphonamidophthalazine (2·1 g.), crystallised from dioxan, had m. p. 236—237°.

The acetyl compound (2 g.) was heated on a water-bath for 1 hr. with alcohol (20 c.c.) containing concentrated hydrochloric acid (8 c.c.). The mixture was diluted with water (80 c.c.) and neutralised with ammonia. The solid obtained was crystallised from alcohol, giving 1-sulphanilamidophthalazine, m. p. and mixed m. p. 242°.

ORGANIC CHEMISTRY DEPARTMENT,
UNIVERSITY OF ADELAIDE, SOUTH AUSTRALIA. [*Received, May 1st, 1956.*]

---

680. *The Mechanism of the Pinacol–Pinacone Rearrangement. Part I. Catalysis by Strong Monobasic Acids.*

By J. F. DUNCAN and K. R. LYNN.

The kinetics of the rearrangement of pinacol to pinacone, with perchloric, nitric, hydrochloric, and toluene-*p*-sulphonic acids in aqueous media, at concentrations between 0·01 and 1·5 molar, and temperatures between 67·8° and 113·5°, are in accordance with the reaction scheme

$$H^+ + P \underset{\text{Fast}}{\rightleftharpoons} HP^+ \xrightarrow[\text{Slow}]{} \text{products}$$

where P represents the pinacol molecule. There is no evidence for any simultaneous alternative reaction route.

ALTHOUGH the mechanism of the pinacol–pinacone rearrangement has been often discussed [1] the reaction kinetics have been studied very little. Bartlett and Brown,[2] Sello,[3] and

[1] See, for example, Bennett, *Ann. Reports*, 1930, **27**, 114; Wallis, "Organic Chemistry," Ed. Gilman, Wiley, New York, 1947, Vol. 1, p. 965; Ingold, "Structure and Mechanism in Organic Chemistry," Bell, London, 1953.
[2] Bartlett and Brown, *J. Amer. Chem. Soc.*, 1940, **62**, 2927.
[3] Sello, Ph.D. Thesis, Univ. of Missouri, 1940.

Criegee and Plate [4] studied the rearrangement of the geometric isomers of 7 : 8-diphenylacenaphthenediols, and the last authors also reported results with 1 : 2-dimethylcyclopentane-1 : 2-diols. Meerburg [5] studied tetra-*p*-chlorobenzpinacol, whilst Bergmann and Schuchardt [6] used various tetra-alkylpinacols. Recently the velocity of rearrangements of benzpinacol has been investigated.[7]

This earlier work was done in acetic acid or other non-aqueous solvents, and with one exception the results are difficult to interpret. Apparently the reaction is unimolecular with respect to the pinacol, and the velocity is proportional to the acid concentration. But it is remarkable that this important reaction has not yet been studied in detail in aqueous acids.

We have determined the rate of rearrangement of pinacol itself under a variety of conditions in aqueous media, and now describe the results of reaction with strong monobasic acids and discuss the evidence they provide for the mechanism of the rearrangement.

Experimental

Reagents.—The pinacol was prepared from acetone,[8] and the hexahydrate so obtained dehydrated.[9] The anhydrous pinacol was twice distilled in all-glass apparatus through a 40-cm. column [the fraction, b. p. 172°, was collected], and stored over calcium chloride.

Hydrochloric and nitric acids were prepared from analytical grade concentrated reagents. The perchloric acid, from A.R. 70% solution, was diluted and standardized with barium hydroxide.[10] The toluene-*p*-sulphonic acid was purified [11] to constant m. p. 107°.

Method.—Below 90° a constant-temperature water-bath with temperature control to better than ±0·1° was used. Aqueous solutions of pinacol were mixed with temperature-equilibrated acids, zero time being taken at half-addition of acid to the glycol. To follow the reaction, samples (5 ml.) were pipetted at various times from the stoppered reaction flasks into a cooled excess of a saturated sodium hydrogen carbonate solution for analysis.

Above 90°, a constant-temperature oil-bath (better than ±0·5°) was used. Cold samples (5 ml.) were pipetted into tubes which were sealed and immersed in the bath for reaction. Rates of reaction were always so slow at room temperature that zero time could be taken as the time when the tubes were immersed in the bath. Likewise, quenching the sample tubes in ice–water was effective for rapidly stopping the reaction. The tube contents were finally rinsed into a cold excess of saturated hydrogen carbonate solution for analysis.

Analysis for Pinacol.—The specific reaction of periodate with α-glycols [12] was employed. 10 ml. of 0·1M-periodic acid [13] were added to each sample in saturated hydrogen carbonate solution, and the mixture was left for 4 hr. at room temperature.[13] No attack by the periodate on the pinacone produced was detected. 10 ml. of 0·1N-sodium arsenite [12] and 1 ml. of 20% potassium iodide solution were then added, and after 10 min. the excess of arsenite was estimated with 0·1N-iodine, a starch indicator being used.

Analysis for Pinacone.—(*a*) For the estimation of pinacone after complete reaction (*i.e.*, ~0·1M-ketone), Smith and Mitchell's titrimetric method [14] was used. (*b*) In the study of pinacone production during reaction, method (*a*) was not sufficiently sensitive and an ultraviolet absorption technique was adopted. Measurements were made at 2800 Å with a 0·5 mm. slit on a Hilger "Uvispek" with 1-cm. quartz cells. The samples were rapidly chilled after the reaction, but not treated with bicarbonate solution. The percentage transmission was compared with that obtained under identical conditions with solutions containing 0·1M-pinacol, acid at the same strength as used in the reaction, and known amounts of pinacone. The degree of absorption obtained with 0·01M-pinacone solution was unaffected within experimental error by the presence of 0·1M-pinacol.

Side Reactions.—With concentrations above about 1·5N of hydrochloric, perchloric, and

[4] Criegee and Plate, *Ber.*, 1939, **72**, 178.
[5] Meerburg, *Rec. Trav. chim.*, 1905, **24**, 131.
[6] Bergmann and Schuchardt, *Annalen*, 1931, **487**, 225.
[7] Gebhardt and Adams, *J. Amer. Chem. Soc.*, 1954, **76**, 3925.
[8] *Org. Synth.*, Coll. Vol. I, 1943, p. 459.
[9] King and Stewart, *Chem. Abs.*, 1931, **25**, 1799.
[10] Smith and Koch, *Ind. Eng. Chem. Anal.*, 1931, **3**, 53.
[11] Vogel, "Textbook of Practical Organic Chemistry," Longmans, London, 1948, p. 532.
[12] Jackman, *Org. Reactions*, 1947, **2**, 341.
[13] Price and Kroll, *J. Amer. Chem. Soc.*, 1938, **60**, 2726.
[14] Smith and Mitchell, *Analyt. Chem.*, 1950, **22**, 750.

nitric acids, a yellow coloration was frequently noticed in the reaction mixtures especially at high temperatures. At 50°, for instance, heating for 100 min. was sufficient to cause a pronounced coloration. Whenever the yield of pinacone was low, distinct coloration was obtained and the results were therefore discarded.

Results

(a) *Single Acids.*—Kinetic runs have been made by following the pinacol loss with four strong monobasic acids, *viz.*, hydrochloric, perchloric, nitric, and toluene-*p*-sulphonic. The first-order rate was always dependent on the concentration of pinacol; the values of the rate constant are given in Table 1.

TABLE 1. *First-order rate constants* [concentrations in mole/l.; k_{exp} in 10^5 sec.$^{-1}$].

Concn.	k_{exp}	Concn.	k_{exp}	Concn.	k_{exp}	Concn.	k_{exp}
$HClO_4$ at 67·8°		$HClO_4$ at 100·0°		HCl at 78·0		*p*-$CH_3{\cdot}C_6H_4{\cdot}SO_3H$ at 78·0	
1·12	2·34	0·31	31·3	0·99	4·36	0·93	3·79
0·95	2·07	0·19	14·8	0·73	2·31	0·64	1·92
0·55	0·96	0·14	13·3	0·46	1·61	0·54	1·57
0·51	0·90	0·09	6·69	0·30	0·89	0·42	1·27
		0·07	5·57	0·13	0·33	0·17	0·54
at 78·0°		0·05	3·48	0·05	0·16		
1·41	13·9						
0·95	5·60	at 113·5°		at 90·0°		at 90·0°	
0·67	4·25	0·71	307	1·13	29·2	0·93	16·0
0·30	1·19	0·50	219	0·91	19·4	0·54	12·1
0·07	0·36	0·29	121	0·73	15·9	0·35	7·32
0·03	0·14	0·19	102	0·46	8·47	0·15	2·88
		0·07	39·4	0·11	1·65	0·14	2·42
at 90·0°		0·03	14·5	0·06	1·00	0·07	1·00
1·13	43·0						
0·76	22·9	HNO_3 at 100°		at 100·0°		at 100·0°	
0·50	13·2	0·40	34·5	0·42	33·9	0·34	27·6
0·39	9·54	0·31	25·0	0·29	22·5	0·18	13·4
0·35	8·56	0·30	23·5	0·21	16·8	0·14	10·1
0·07	1·15	0·10	7·69	0·10	7·86	0·07	5·02
				0·08	5·02		
				0·05	3·85		
				0·01	0·56		

TABLE 2. *Comparison of* (A) *rate of formation of pinacone with* (B) *rate of loss of pinacol, both at* 100° [rates are expressed as $a/(a-x)$; time in sec.].

				0·295M-*Hydrochloric acid*				
t	900	1500	2125	2915	3775	4390	5095	5815	9955
A	1·13	1·26	1·45	1·66	1·88	2·22	2·43	2·66	12·1
B	1·14	1·27	1·51	1·70	1·90	2·14	2·75	2·80	12·0
				0·339M-*Toluene*-p-*sulphonic acid*				
t	1080	1800	2580	4560	8340	8760			
A	1·51	1·77	2·28	3·50	8·35	12·0			
B	1·56	1·77	2·05	3·30	8·55	11·8			

(b) *Pinacone Production.*—The rate of formation of pinacone was sometimes determined at the same time as the rate of loss of pinacol (see Table 2); the two rates were identical within the limits of experimental error. It was, however, possible to check that these were the same only at concentrations above about 0·01M-pinacone because of instrumental limitations. In most of the kinetic runs followed by pinacol analysis, the initial concentration of pinacol was 0·01—0·1M.

(c) *Acid–Salt Mixtures.*—The reaction was also followed by determining the loss of pinacol with acid–salt mixtures of constant ionic strength and variable concentration either of hydrogen ion or of anion. The results for mixtures of either hydrochloric acid or perchloric acid and their sodium and potassium salts respectively are plotted in Fig. 1 (curve *F*). The full line is that obtained for the pure acids, the results for which were identical within the limits of error at such low ionic strengths. The points for pure nitric acid are also shown.

Discussion

It is generally accepted that the first stage of this reaction is proton addition to the hydroxyl group, *viz.*,

$$H^+ + P \rightleftharpoons HP^+ \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where P represents the pinacol molecule. This equilibrium is believed to be set up very rapidly. Without detailing the final stage (concerning which the kinetics alone will provide no evidence), we may write the rearrangement as proceeding either by (*a*) unimolecular decomposition of the pinacol conjugate acid :

$$HP^+ \xrightarrow{\text{Slow}} A \xrightarrow{\text{Fast}} \text{products} + H^+ \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

or (*b*) bimolecular reaction with the solvent :

$$HP^+ + H_2O \xrightarrow{\text{Slow}} A \xrightarrow{\text{Fast}} \text{products} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where A is the transition state. The reaction rate in mechanism (2) will clearly depend on the concentration of HP^+ in the steady state, and may be shown [15] to be

$$R = k[HP^+] = kK_a[H^+][P]\gamma_{H^+}\gamma_P/\gamma_{HP^+} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where R is the reaction rate, K_a is the thermodynamic equilibrium constant of reaction (1), k is the rate constant, and the γ's are the appropriate activity coefficients of the various species in the mixture.

When $kK_a = k_1$ the experimentally determined rate constant k_{exp}, given in Table 1, is given by

$$k_{exp} = k_1[H^+]\gamma_{H^+}\gamma_P/\gamma_{HP^+} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

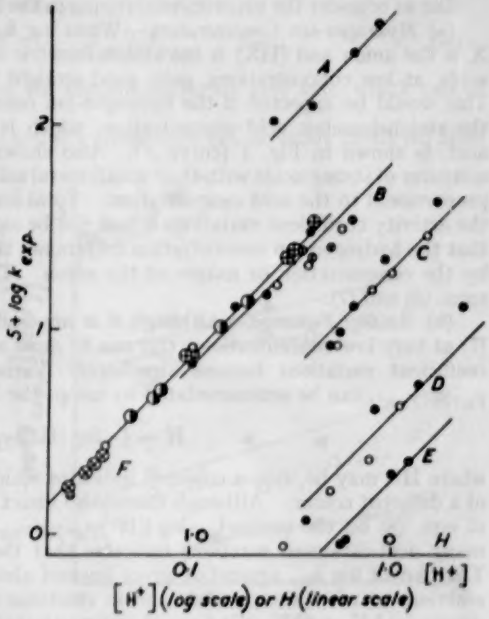


FIG. 1. log k_{exp} *plotted as a function of the acidity constant H.* ○, *Hydrochloric acid;* ●, *perchloric acid;* ⓘ, *nitric acid. Curves A,* 113·6°; *B,* 100·0°; *C,* 90·0°; *D,* 78·0°; *E,* 67·8°. *In curve F,* log k_{exp} *at* 100° *is plotted as a logarithmic function of* [*acid*] *for mixtures of* (a) *hydrochloric acid and sodium chloride at ionic strength* 0·1 (*points* ○), (b) *perchloric acid and potassium perchlorate at an ionic strength of* 0·05 (*points* ⊗), (c) *pure nitric acid* (*points* ⊕), *and* (d) *toluene-*p*-sulphonic acid* (*points* ◑). *The points marked* ⊖ *were determined at* [NaCl] = 0·03M *and ionic strength* 0·13, *made up with mixtures of perchloric acid and potassium perchlorate. The lines for curves A—E are drawn with unit slope, and for curve F the line is that obtained for all pure monobasic strong acids below concentrations of* 0·1M.

[15] Bell, "Acid–Base Catalysis," Oxford Univ. Press, 1942.

By comparison, the reaction rate corresponding to eqn. (3) would be

$$R = k\{HP\}\{H_2O\}$$
$$= k_1[H^+][P]\{H_2O\}\,\gamma_{H^+}\gamma_P \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$
$$= k_{exp}[P]$$

where $$k_{exp} = k_1[H^+]\gamma_P{}^+\gamma_H\{H_2O\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Let us consider the experimental results in the light of eqns. (5) and (7).

(a) *Hydrogen-ion Concentration.*—When log k_{exp} was plotted against log [HX] (where X is the anion and [HX] is the stoicheiometric concentration of HX) all the monobasic acids, at low concentrations, gave good straight lines which were practically coincident. This would be expected if the hydrogen-ion concentration were assumed to be equal to the stoicheiometric acid concentration, which is reasonable. A typical plot, for nitric acid, is shown in Fig. 1 (curve *F*). Also shown are the rate constants obtained with mixtures of strong acids with their alkali-metal salts, for which the rate constants were also proportional to the acid concentration. Total ionic strength was always quite small and the activity coefficient variations would not be significant. This result therefore confirms that the hydrogen-ion concentration determines the rate of reaction, which is uninfluenced by the concentration or nature of the anion. This result would be expected from both eqns. (5) and (7).

(b) *Acidity Function.*—Although it is impossible to distinguish between eqns. (5) and (7) at very low concentrations, this can be done at high concentrations where the activity coefficient variations become significant. Variations in the activity coefficient ratio, $\gamma_{H^+}\gamma_P/\gamma_{HP^+}$, can be accommodated by use of the Hammett acidity function [16]

$$H = (-\log [H^+])\gamma_{H^+}\gamma_{B^-}/\gamma_{HB} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where HB may be, say, a coloured indicator which dissociates to give a conjugate base B of a different colour. Although there is no direct dependence of the right-hand expression of eqn. (8) on the product $-\log([H^+]\gamma_{H^+}\gamma_P/\gamma_{PH^+})$, use of *H* instead of this quantity in many acid-catalysed reactions indicates that the two expressions vary in like manner. The plot of log k_{exp} against *H* gives lines of almost unit slope in most H^+-ion catalysed reactions at room temperature and in reactions at higher temperatures [16] although *H* is determined [17] at 25°. We have therefore plotted log k_{exp} against *H*, as in Fig. 1 (curves *A*—*E*), for hydrochloric, perchloric, and nitric acids, the values of *H* quoted by Hammett and Paul [17] for these acids at 25° being used. The plots of the different acids are almost coincident, and nearly of unit slope. Long and McIntyre [18] have recently re-emphasized that the slope of the acidity function plot would be expected to be exactly unity only when the term γ_P/γ_{HP^+} in eqn. (4) changes precisely as does the term γ_{B^-}/γ_{HB} in eqn. (8). In general, the slopes will all differ slightly from unity and from one another. In the present experiments these differences are hardly greater than experimental error (which has a variable contribution because of the use of acidity function data at 25° for kinetic experiments made at 67·8—113·5°). This probably accounts for the fact that the slope for hydrochloric acid is less than that for perchloric acid, whereas it should be greater. Salt effects are therefore small in our system, and according to Long and McIntyre [18] these strong acids behave thus with a wide series of neutral molecules.

If eqn. (7) were obeyed, we should not expect plots such as Fig. 1 (curves *A*—*E*) to be obtained, since $\{H_2O\}$ is not inversely proportional to γ_{HP^+}, but is a complicated function of the acid strength and the osmotic coefficient of the acid solution.[19] Insertion of tabulated data in eqn. (6) indicates that, were that equation obeyed, the highest acid concentration (~1·5M) is sufficient to cause deviations, of significant magnitude,

[16] Hammett and Deyrup, *J. Amer. Chem. Soc.*, 1932, **54**, 2721.
[17] Hammett and Paul, *ibid.*, 1934, **56**, 827.
[18] Long and McIntyre, *ibid.*, 1954, **76**, 3240, 3243.
[19] Harned and Owen, "The Physical Chemistry of Electrolyte Solutions," Reinhold, New York, 1950.

in linearity and slope. Eqn. (6) is clearly not obeyed. Analogous results for sulphuric acid confirm this, for only small deviations from linearity and unit slope were evident over a much larger concentration range {$0{\cdot}1 < [H_2SO_4] < 5$ molar; see Fig. 1 of next paper}.

(c) *Calculation of Variation in Activity Coefficient Ratio.*—Although the kinetic effect of an acid in these reactions is dependent on the concentration and activity of the hydrogen ion alone, a thermodynamic evaluation of the activity of the hydrogen ion-anion pair ($\gamma^{\pm}_{HX}$) only can be made (where X is the anion of the monobasic acid). But we may write

$$\log(\gamma_{H^+}\gamma_P/\gamma_{HP^+}) = \log(\gamma_{H^+}\gamma_X/\gamma_{HP^+}\gamma_X) + \log\gamma_P \quad . \quad . \quad . \quad (9)$$

$$= 2\log(\gamma^{\pm}_{HX}/\gamma^{\pm}_{HPX}) + \log\gamma_P \quad . \quad . \quad . \quad (10)$$

where $\gamma^{\pm}_{HPX}$ is the activity coefficient of the pinacol conjugate acid salt, which can of course be completely dissociated.

Now variations in the values of these activity coefficients can be safely predicted from

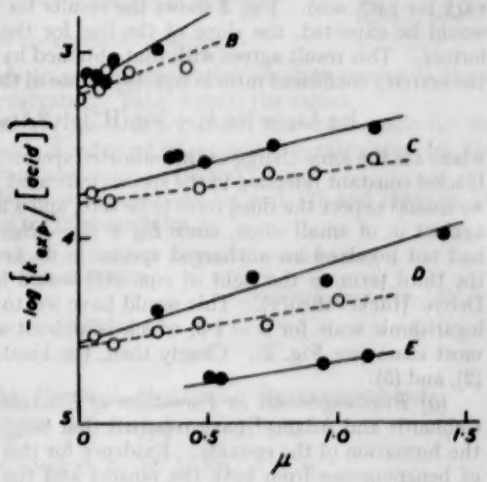


FIG. 2. $\log k_{exp}/[acid]$ *as a function of ionic strength* (μ). ○, *Hydrochloric acid*; ●, *perchloric acid*. *Curves* B, 100·0°; C, 90·0°; D, 78·0°; E, 67·8° c.

the known trends of the activity coefficients of simple acids and salts, since the conditions of the experiment are such that simple approximations can reliably be made, thus:

(i) Since the HP^+ concentration is very small compared with that of the acid, then

$$\gamma^{\pm}_{HX} = \gamma^{\circ\pm}_{HX}$$

where $\gamma^{\circ\pm}_{HX}$ is the activity coefficient of the pure acid in solutions of the same ionic strength.

(ii) For a similar reason, the contribution to γ_P of terms involving interaction between pinacol molecules will be negligible, and we can write [20]

$$\log\gamma_P = k_s[HX] \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

where k_s is a constant.

(iii) The value of $\gamma^{\pm}_{HPX}$, the activity coefficient of HPX in solutions of low concentration of HPX in high concentrations of acid, can be evaluated in terms of $\gamma^{\pm}_{HX}$ and $\gamma^{\pm}_{HPX}$, the activity coefficient of pure HPX, by application of Harned's rule [19,21] which will certainly be valid for such mixtures of a base with its conjugate acid. Hence,

$$\log\gamma^{\pm}_{HPX} = \tfrac{1}{2}(\log\gamma^{\circ}_{HX} - \log\gamma^{\circ}_{HPX}) \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

[20] Long and McDevitt, *Chem. Rev.*, 1952, **51**, 119.
[21] Glueckauf, *Nature*, 1949, **163**, 414.

from which

$$\begin{aligned}\log(\gamma_{H^+}\gamma_P/\gamma_{HP^+}) &= 2\log\gamma^{\circ\pm}{}_{HX} - (\log\gamma^{\circ}{}_{HX} + \log\gamma^{\circ}{}_{HPX}) + k_s[HX] \\ &= \log\gamma^{\circ\pm}{}_{HX} - \log\gamma^{\circ}{}_{HPX} + k_s[HX] \\ &= \alpha_{12}[HX] + k_s[HX] \\ &= [HX](\alpha_{12} + k_s) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)\end{aligned}$$

where α_{12} is the Harned coefficient, and is constant over wide changes of concentration.[19]

Hence we may conclude that, since

$$\begin{aligned}\log(k_{exp}/[H]) &= \log k_1 + \log(\gamma_{H^+}\gamma_P/\gamma_{HP^+}) \\ &= \log k_1 + [HX](\alpha_{12} + k_s) \quad . \quad . \quad . \quad . \quad . \quad (14)\end{aligned}$$

then $\log(k_{exp}/[H^+])$ should vary linearly with HX. Also, since α_{12} is generally positive and dependent on the nature of the acid HX, the slope of this plot will be positive, and vary for each acid. Fig. 2 shows the results for perchloric and hydrochloric acid, and as would be expected, the slope of the line for the latter acid is greater than that for the former. This result agrees with that obtained by the conventional approach of evaluating the activity coefficient ratio in eqn. (5) by use of the Debye–Hückel equation, for

$$\log k_{exp} = \log k_1 + \log[H^+] + 2Az_H z_P \mu^{\frac{1}{2}} + (B_{H^+} + B_P - B_{HP^+}) \quad . \quad (15)$$

where z is the ionic charge of the indicated species, μ is the ionic strength, and B the Debye–Hückel constant referring to the species indicated. Since the pinacol molecule is uncharged we should expect the third term to be zero, and a linear plot to be obtained for $\log k_{exp}/[H^+]$ against μ, of small slope, since $B_H + B_P - B_{HP^+}$ is small (see Fig. 2). If the reaction had not involved an uncharged species in its first stage the minimum possible value for the third term on the right of eqn. (13) would have been $\mu^{\frac{1}{2}}$ (A being taken as 0·5 from Debye–Hückel theory). This would have led to a change in $\log k_{exp}$ by 1·5 units on the logarithmic scale for $\mu = 1{\cdot}5$, which is at least a factor of 5 more than that obtained in most cases (see Fig. 2). Clearly then, the kinetics are in accordance with equations (1), (2), and (5).

(d) *Rearrangements by Formation of Epoxide.*—In the rearrangement of benzpinacol, Gebhardt and Adams [7] have reported that 80% of the reaction proceeds at 75° by way of the formation of the epoxide. Evidence for this was adduced from the rate of production of benzpinacone from both the pinacol and the epoxide which was followed by spectro-

TABLE 3. *Rate constants calculated from data simultaneously from* (A) *the rate of loss of pinacol and* (B) *the rate of production of pinacone at* 100° [k_{exp} in 10^5 sec.$^{-1}$].

Acid	k_{exp} from A	k_{exp} from B	Acid	k_{exp} from A	k_{exp} from B
0·295M-HCl	20·2	21·9	0·339M-Me·C_6H_4·SO_3H ...	28·4	31·3

photometric estimation of the benzpinacone. The same method used by us with pinacone itself gave the rate constants quoted in Table 3 which show that there is no significant difference between the rate of pinacol loss and the rate of pinacone production. It is therefore clear that we are concerned only with a single reaction route.

This conclusion does not exclude the possibility of the rearrangements' proceeding by the reaction

$$P + H^+ \overset{\text{Fast}}{\rightleftharpoons} HP^+ \overset{\text{Fast}}{\rightleftharpoons} \text{Epoxide} + H_3O^+ \quad . \quad . \quad . \quad . \quad (16)$$

$$\downarrow$$

$$\text{Pinacone}$$

but the second stage would have to be fast (compared with the rate of rearrangement) and the last stage would be the rate-determining step. For the epoxide, if present, would probably be oxidized by periodic acid (*via* conversion into pinacol) and included in the pinacol analysis. However, it is hardly possible for the epoxide mechanism to make any

significant contribution to the mechanism since one would expect it to be completely converted into pinacol by the catalysing acid. It is also known [22] that dilute aqueous acids convert alicyclic epoxides into pinacols, and one would not have expected the tetramethyl pinacol to act differently. On the other hand, one might have expected that the tetraphenylpinacol carbonium ion $[Ph_2C(OH)\cdot C^+Ph_2]$ would be much more stable than the corresponding tetramethyl ion even in aqueous acid, but especially so in the non-aqueous solvent used by Gebhardt and Adams [7] for the former. This would explain satisfactorily these authors' finding that part of the rearrangement of the tetraphenylpinacol proceeds *via* the epoxide. But with the tetramethylpinacol, the evidence suggests that the epoxide mechanism is not significant.

TABLE 4. *Values of* k_1 (10^5 sec.$^{-1}$)

Temp.	$HClO_4$	HCl	HNO_3	*p*-Me·C_6H_4·SO_3H	Mean
67·8°	1·3 ± 0·1	—	—	—	1·3 ± 0·1
78·0	2·7 ± 0·2	2·6 ± 0·05	—	3·1 ± 0·1	2·8 ± 0·17 *
90·0	18·0 ± 1·0	16·0 ± 1·0	—	17·0 ± 1·0	17·0 ± 1·0 *
100·0	65·0 ± 2·0	61·0 ± 3·0	66·0 ± 2·0	68·0 ± 2·0	65·0 ± 2·3 *
113·5	450·0 ± 50·0	—	—	—	450·0 ± 50·0

* The limits quoted are standard deviations.

(e) *Arrhenius Plot.*—By extrapolation to zero concentration of plots similar to those in Fig. 2, values of k_1 in eqn. (5) can be evaluated. Table 4 gives the values.

A plot of log k_1 (mean values) against $1/T$ leads to a value of 32·7 kcals./mole for the energy of activation. This compares with a value of 31 kcals./mole calculated for the rearrangement of benzpinacol [7] by reactions analogous to (1) and (2).

The foregoing results are in accordance with reactions (1) and (2) and there is no evidence of any reaction involving any other intermediates.

CHEMISTRY DEPARTMENT AND TRACER ELEMENTS SECTION OF THE COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION, UNIVERSITY, MELBOURNE.

[*Received, July 19th*, 1955.]

[22] Bartlett and Bayley, *J. Amer. Chem. Soc.*, 1938, **60**, 2416.

---

681. *The Mechanism of the Pinacol–Pinacone Rearrangement. Part II.* Catalysis by Sulphuric Acid.*

By J. F. DUNCAN and K. R. LYNN.

The rearrangement of pinacol to pinacone has been followed in sulphuric acid and in mixtures of hydrochloric acid, sulphuric acid, sodium hydrogen sulphate, and sodium sulphate at different ionic strengths; it is catalysed solely by the hydrogen ion, and the kinetic results generally confirm the conclusions of the preceding paper. The bisulphate ion does not significantly catalyse the reaction, but the sulphate ion retards it.

EXPERIMENTAL

THE experimental procedures were as described in the preceding paper.

(a) *Pinacol Loss.*—The reaction was studied with 0·001M—6·33M sulphuric acid solutions within the temperature range 72·6—154° c. The first-order rate constants obtained are given in Table 1.

TABLE 1. *First-order rate constants for catalysis by sulphuric acid* (k_{exp} in 10^5 sec.$^{-1}$).

	72·6°				103·0°							
Molarity ...	6·33	4·83	1·14	0·67	0·910	0·850	0·660	0·300	0·157	0·078	0·010	0·001
k_{exp}	25·4	10·5	2·01	1·56	69·3	67·6	46·0	27·2	14·5	7·03	0·95	0·072

	124·5°					154·0°			
Molarity ...	0·157	0·085	0·077	0·036	0·018	0·018	0·005	0·002	0·001
k_{exp}	222	113	106	34·7	21·9	484	133	67·4	33·9

* Part I, preceding paper.

(b) *Pinacone Production.*—Table 2 shows the formation of pinacone and the simultaneous loss of pinacol. The values of k_{exp} calculated from these results were respectively, $11{\cdot}81 \times 10^{-4}$ sec.$^{-1}$ and $11{\cdot}40 \times 10^{-4}$ sec.$^{-1}$, which, like the results of the previous paper, are in accordance with a single reaction route.

TABLE 2. *Comparison of* (A) *rate of formation of pinacone with* (B) *rate of loss of pinacol in* 0·14M-*sulphuric acid at* 103° [rates expressed as $a/(a - x)$; t in sec.].

t	5000	7500	11,000	14,750	23,000	25,400
A	1·88	2·24	3·23	4·80	16·30	31·71
B	1·95	2·13	3·34	4·90	15·60	30·86

(c) *Acid–Salt Mixtures.*—The results are given in Table 3 of several experiments with mixtures of hydrochloric acid with either sodium sulphate or sodium hydrogen sulphate and of sulphuric acid with sodium sulphate. Frequently sodium chloride was also added to adjust the ionic strength.

TABLE 3. *First-order rate constants* (in 10^5 sec.$^{-1}$) *with acid–salt mixtures at* 100°.

Molarity H_2SO_4	$NaHSO_4$	Na_2SO_4	NaCl	HCl	k_{exp}	Fig.
—	—	0·025	0·025	0·04	1·65	1
—	—	0·020	0·04 *	0·04	1·54	
—	—	0·010	0·07	0·04	2·10	
—	—	0·009	0·058	0·04	2·00	
—	—	0·005	0·095	0·04	2·25	
—	—	0·0014	0·095	0·04	2·43	
—	—	0·001	0·097	0·04	2·80	
0·005	—	0·045	—	—	0·06	2
0·01	—	0·04	—	—	0·14	
0·02	—	0·03	—	—	0·50	
0·03	—	0·02	—	—	0·89	
0·04	—	0·01	—	—	2·42	
—	0·01	—	0·09	0·03	2·12	3
—	0·02	—	0·07	0·02	1·26	
—	0·03	—	0·05	0·01	0·87	
—	0·04	—	0·03	—	0·58	

* LiCl.

DISCUSSION

(a) *Sulphuric Acid.*—In aqueous sulphuric acid, even if the rearrangement is catalysed solely by hydrogen ions, we may expect the variation of rate constant to be a complicated function of the stoicheiometric H_2SO_4 concentration quite apart from variations in ionic activity which are also serious in solutions containing multivalent ions.

We may, however, calculate with reasonable accuracy the hydrogen-ion concentration in dilute solutions by using the values of the mass products, $K_1 = [H^+][HSO_4^-]/[H_2SO_4]$ and $K_2 = [H^+][SO_4^{2-}]/[HSO_4^-]$, interpolated from Young and Blatz's data.[1] These values may be in error by 10%, due to uncertainty in the interpolation at low concentration, but this would not cause an error in the calculated hydrogen-ion concentration of more than 5%. Fig. 1 (curves *A*—*D*), in which the rate constants are plotted, shows that the reaction is dependent on the first power of $[H^+]$ over a very wide range of concentration, although there are some deviations at high concentrations as might be expected from activity effects.

Use of the acidity function[2] for sulphuric acid confirms this conclusion. The plots of rate constant against acidity function shown in Fig. 1 (curves *a*—*d*) are straight lines of nearly unit slope. In Fig. 1 (curves *C*, *c*) the lines (at 103°) are those expected from the results with strong monobasic acids (see preceding paper), allowance being made in each case for a small difference between the temperatures at which these and the previous results were determined. There can be no doubt that the principal catalysing species is the hydrogen ion.

(b) *Catalysis by Solutions of Different Ionic Composition.*—The ionic composition of

[1] Young and Blatz, *Chem. Rev.*, 1949, **44**, 102.
[2] Hammett and Deyrup, *J. Amer. Chem. Soc.*, 1932, **54**, 2721.

sulphuric acid varies [1] with concentration from solutions which contain practically no bisulphate ions to solutions containing practically no sulphate ions. Systematic variation of the relative concentration of these ions at constant ionic strength is thus difficult, especially because of the low dissociation constant of bisulphate ion and the presence of bivalent as well as univalent ions. A reasonably wide variation in the relative concentrations of these ions at different ionic strengths was, however, studied by carrying out the reaction at 100° in the following mixtures: (i) sodium sulphate–hydrochloric acid, sometimes with sodium or lithium chloride (Fig. 1), (ii) sodium sulphate–sulphuric acid (Fig. 2), (iii) sodium hydrogen sulphate–sodium chloride–hydrochloric acid (Fig. 3).

A value of 10^{-2} being assumed for the dissociation constant of HSO_4^- the concentrations of the H^+, SO_4^{2-}, and HSO_4^- ions can be calculated. As this calculation takes no account of the activity coefficients of the mixtures there must be some inaccuracy. The estimated errors for an error in K_2 of twofold are given in Table 4. The relative errors reported are

TABLE 4. *Estimated errors (factor of 2 in the value of K_2)* (concentrations in g.-ions/l.).

Mixture Fig.	Absolute errors				Relative errors			
	H^+	SO_4^{2-}	HSO_4^-	μ	H^+	SO_4^{2-}	HSO_4^-	μ
1	0·003	0·0028	0·0025	0·005	0·0025	0·0017	0·0012	0·003
2	0·006	0·007	0·006	0·025	0·007	0·013	0·007	0·037
3	0·008	0·008	0·010	0·014	0·005	0·006	0·007	0·009

the changes in the differences between concentrations at the opposite ends of the plots of Figs. 1—3. The general shape of the curves cannot therefore be open to question even though there are relatively large errors in the absolute concentrations.

In Table 5, the values of $[H^+]$, $[HSO_4^-]$, $[SO_4^{2-}]$, and μ are given, for a series of mixtures, calculated from the results given in Table 3 (Fig. 1). In all mixtures the concentrations of bisulphate and sulphate ions are respectively less than 0·017M and 0·008M, even though the ionic strength varies by about 40%. At such low concentrations the presence of neutral electrolyte *per se* would not be expected to influence the rate constant (see previous paper), and it is not therefore surprising that in the mixtures in which the concentrations

TABLE 5.

$[H^+]$	$[HSO_4^-]$	$[SO_4^{2-}]$	μ	k_{exp} (10^5 sec.$^{-1}$)	$[H^+]$	$[HSO_4^-]$	$[SO_4^{2-}]$	μ	k_{exp} (10^5 sec.$^{-1}$)
0·023	0·017	0·008	0·105	1·65	0·036	0·004	0·001	0·142	2·25
0·026	0·015	0·006	0·112	1·54	0·039	0·001	0·0003	0·137	2·43
0·033	0·008	0·002	0·125	2·10	0·039	0·0008	0·0002	0·138	2·80
0·034	0·007	0·004	0·108	2·00					

of bisulphate and sulphate ions are low, the rate constants agree within experimental error with those obtained both with pure sulphuric acid and with strong monobasic acids. This is seen in Fig. 1 *C*.

When, however, the concentration of either bisulphate or sulphate ions becomes large a pronounced lowering of the reaction rate occurs, as the results with mixtures (ii) and (iii) (Table 3) show. These results were determined by systematically varying the stoicheiometric concentration of one or more of the constituent salts or acids, in each case with sufficient predetermined conditions to make the ionic composition dependent on only one variable. Thus, in Fig. 2 we have that $[Na_2SO_4] + [H_2SO_4] = 0·05$, whilst for Fig. 3, $3[NaHSO_4] + [HCl] + [NaCl] = 0·15$ and $[HCl] + [NaHSO_4] = 0·04$. We can therefore plot curves of the ionic concentrations of bisulphate, sulphate, and hydrogen ions, and of the ionic strength (μ) as functions of the observed rate constant, $k_{exp}/[H^+]$. These plots are shown in Figs. 2 and 3. They were calculated from smoothed plots of $k_{exp}/[H^+]$ against one of the systematically varied concentrations.

(c) *Effect of Ionic Strength.*—We may now interpolate values for $[H^+]$, $[HSO_4^-]$, $[SO_4^{2-}]$, and $k_{exp}/[H^+]$ for constant values of μ by using Figs. 2 and 3. The data are given in Table 6; $k_{exp}/[H^+]$ is obviously not constant at a given ionic strength, as is frequently obtained with reactions, catalysed by hydrogen ions, in mixtures in which only univalent ions are present. This variation is undoubtedly due to the presence of variable and relatively large amounts of bivalent ions.

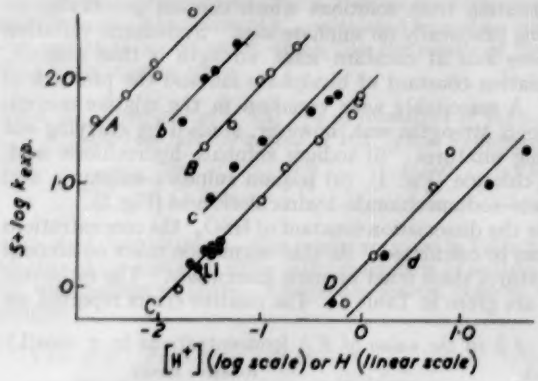


FIG. 1. log k_{exp} *plotted as* (a) *a logarithmic function of* $[H^+]$ (*capital letters*, ○) *and* (b) *as a linear function of the acidity function H* (lower case letters, ●), *both for pure sulphuric acid*; (c) *the calculated* $[H^+]$ *for* $[Na_2SO_4] + [NaCl] + [HCl] = 0{\cdot}14$ (◎). *Curves Aa*, 154°; *Bb*, 124·5°; *Cc*, 103°; *Dd*, 72·6° c. *The lines at* 103° *are those obtained with strong monobasic acids* (*see previous paper*), *allowance being made for the small difference in temperature. The point marked* Li *indicates that lithium chloride was substituted for sodium chloride in mixture* (*c*). *The acidity function scale is negative and displaced by* 0·3 *unit.*

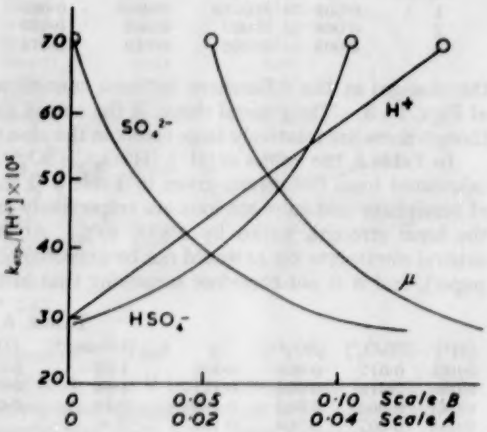


FIG. 2. *Calculated variation in* $[H^+]$, $[HSO_4^-]$, $[SO_4^{2-}]$ (*scale* A), *and* μ (*scale* B) *for a series of mixtures in which* $[H_2SO_4] + [Na_2SO_4] = 0{\cdot}05$M *at* 100° *for different values of* $k_{exp}/[H^+]$. *The latter values were obtained from smoothed curves of* $k_{exp}/[H^+]$ *plotted against* $[H_2SO_4]$. *The points* ○ *are those obtained for* $[Na_2SO_4] = 0$.

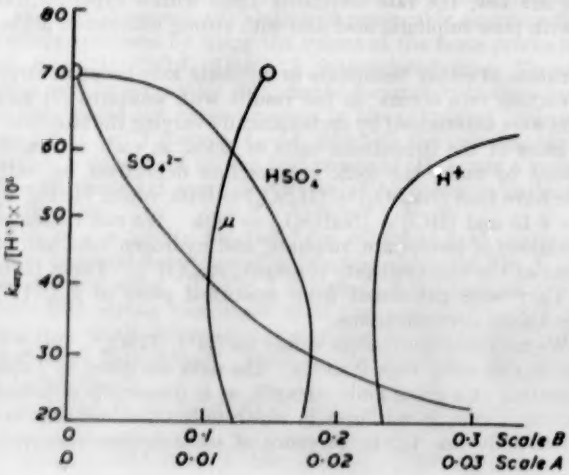


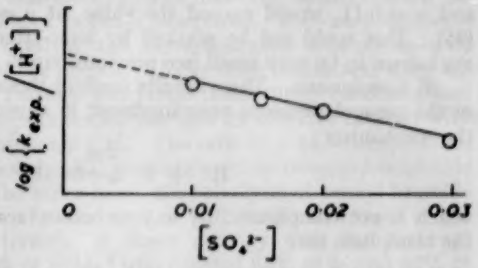
FIG. 3. *Calculated variation in* $[H^+]$, $[HSO_4^-]$, $[SO_4^{2-}]$ (*scale* A), *and* μ (*scale* B) *for a series of mixtures in which* $3[NaHSO_4] + [HCl] + [NaCl] = 0{\cdot}15$M *and* $[NaHSO_4] + [HCl] = 0{\cdot}04$M *at* 100° *for different values of* $k_{exp}/[H^+]$. *The latter values were obtained from smoothed curves of* $k_{exp}/[H^+]$ *plotted against* [HCl]. *The points* ○ *are those obtained for pure hydrochloride acid at* $[HCl] = 0{\cdot}04$M, $\mu = 0{\cdot}15$, *for which it is known that the presence of sodium chloride has no effect* (*see previous paper*).

TABLE 6. *Values of* $k_{exp}/[H^+]$ *at constant ionic strength* (concns. in g.-ions/l.).

μ	H^+	HSO_4^-	SO_4^{2-}	$10^5 k_{exp}/[H^+]$	Fig. used.
0·11	0·003	0·024	0·027	35	2
0·11	0·023	0·018	0·009	39	3
0·12	0·006	0·020	0·031	33	2
0·12	0·023	0·015	0·0041	52	3
0·13	0·003	0·014	0·036	31	2
0·13	0·036	0·011	0·0011	63	3

(d) *Effect of Sulphate Ion.*—Table 6 suggests that the effect of the sulphate ion in lowering the rate constant is much larger than that of the bisulphate ion. This is more clearly seen in Figs. 2 and 3. In both Figs., low values of $k_{exp}/[H^+]$ correspond to very large concentrations of sulphate ion. Likewise in Fig. 2, $k_{exp}/[H^+]$ approaches the value obtained in pure sulphuric acid and in all strong monobasic acids ($68 \pm 2{\cdot}3$)* at the same hydrogen-ion concentration when $[SO_4^{2-}] < 0{\cdot}01$M; whilst in Fig. 3, $k_{exp}/[H^+]$ approaches the value obtained in 0·04M hydrochloric acid (70 ± 2) in the presence or absence of neutral

FIG. 4. $\log k_{exp}/[H^+]$ *plotted as a function of* $[SO_4^{2-}]$ *for* $\mu = 0{\cdot}115$.



salt (see previous paper) when $[SO_4^{2-}] < 0{\cdot}05$. In both cases the concentration of bisulphate ion is large, and we may conclude from these figures that it does not significantly depress or accelerate the reaction at these concentrations. It cannot be more than a tenth as effective as the sulphate ion in depressing the reaction rate. This agrees with the results of Fig. 1 *C*, in which $[SO_4^{2-}] < 0{\cdot}008$M.

The solutions used to obtain the results recorded in Fig. 3 were made up so that the sulphate-ion concentration changed as much as possible with only small changes in the concentrations of the other constituents. There is clearly a wide range ($20 < k_{exp}/[H^+] < 50$) in which μ, $[HSO_4^-]$, and $[H^+]$ are sensibly constant. The values for these quantities obtained by interpolation at various points in this range are given in Table 7. (The absolute accuracy is probably not better than $\pm 10\%$ but the relative values are significant to the number of figures indicated.)

TABLE 7. *Variation of* $k_{exp}/[H^+]$ *with* $[SO_4^{2-}]$ (concentration in g.-ions/l.).

$[SO_4^{2-}]$	$[H^+]$	$[HSO_4^-]$	μ	$10^5 k_{exp}/[H^+]$
0·01	0·0232	0·180	0·110	37·5
0·015	0·0230	0·185	0·112	37·0
0·02	0·0245	0·185	0·115	27·0
0·03	0·0248	0·180	0·121	21·0

Although there is some variation in μ, this is not large enough to give the nearly twofold change in $k_{exp}/[H^+]$, nor is the change obtained in the sense expected for $k_{exp}/[H^+]$ frequently increases as μ increases.[3] When the values of $\log (k_{exp}/[H^+])$ are plotted against $[SO_4^{2-}]$, however, a straight line is obtained (Fig. 4). This reflects a variation in $\log (\gamma_{H^+}/\gamma_{HP^+})$, since changes in γ_{P} will be smaller in comparison. Although such a result would probably not have been obtained at higher ionic strengths and sulphate-ion concentrations, it is satisfying that the dependence on sulphate-ion concentration follows a Harned type expression for γ_{H^+} and γ_{HP^+}, *viz.*, $\log (\gamma_{H^+}/\gamma_{HP^+})_\mu = \log (\gamma^\circ_{H^+}/\gamma^\circ_{HP^+})_\mu + A[SO_4^{2-}]$,

* The factor 10^5 is omitted through the discussion, for brevity.

[3] See, for example, Brönsted and Wynne-Jones, *Trans. Faraday Soc.*, 1929, **25**, 59.

where γ°_{H} and $\gamma^{\circ}_{HP^+}$ refer to the same mixture with zero concentration of sulphate ion, and A is a constant. For, when $[SO_4^{2-}]$ is zero, $\log(\gamma^{\circ}_{H^+}/\gamma^{\circ}_{HP^+}) = \log(k_{exp}/[H^+])$ (at $\mu = 0{\cdot}11$) $= 53$ (obtained by extrapolation) which compares with the value of $68 \pm 2{\cdot}3$, obtained with strong monobasic acids when $\mu < 0{\cdot}15$.

(e) *Effect of Bisulphate Ion.*—From the previous results we can conclude that the effect of the concentration of sulphate ion in lowering the reaction rate is small for $[SO_4^{2-}] < 0{\cdot}008$, and $\mu < 0{\cdot}15$. In this region (Fig. 2), however, the rate constant, $k_{exp}/[H^+]$, is lower than that expected for pure sulphuric acid even though the concentration of bisulphate ion is greater than 0·04M. If there were any significant catalysis by the bisulphate ion, we should have expected a maximum or at least a hump in the bisulphate concentration curve. It is, of course, true that the lowering effect of the sulphate ion might mask any catalysis by bisulphate ion but the latter would require a specific rate constant of less than 2% of that for the hydrogen ion. We therefore conclude that there is no evidence for general acid catalysis by the bisulphate ion. This conclusion is confirmed by Fig. 4. For if the bisulphate ion significantly catalyses the reaction, the value of $k_{exp}/[H^+]$, at $[SO_4^{2-}] = 0$ and $\mu = 0{\cdot}11$, would exceed the value, at $\mu = 0$, obtained for strong monobasic acids (65). This could not be masked by ionic-strength effects at low concentrations which are known to be very small (see previous paper).

(f) *Conclusions.*—These results confirm those of the previous paper, that the kinetics of the pinacol–pinacone rearrangement in aqueous acid solutions are in accordance with the mechanism:

$$H^+ + P \underset{}{\overset{\text{Fast}}{\rightleftharpoons}} HP^+ \xrightarrow{\text{Slow}} \text{products}$$

which is not complicated by any secondary reaction. The reaction is not catalysed by the bisulphate ion.

CHEMISTRY DEPARTMENT AND TRACER ELEMENTS SECTION OF THE COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANIZATION, UNIVERSITY, MELBOURNE, AUSTRALIA. [*Received, July 19th, 1955.*]

---

682. *Studies on Phosphorylation. Part XIV.* The Solvolysis by Phenols of Benzyl Phosphates.*

By G. W. KENNER and J. MATHER.

The reaction between phenol and benzyl diphenyl phosphate leading to a mixture of *o*- and *p*-benzylphenol and diphenyl hydrogen phosphate has been studied; it is accelerated by the addition of acids. The similar reactions of dibenzyl phenyl phosphate and of tribenzyl phosphate are slower, whereas that of tetrabenzyl pyrophosphate is much faster. The process provides a useful method for the removal of benzyl protecting groups.

THE synthesis of numerous phosphates and polyphosphates has been achieved in this laboratory by use of benzylated intermediates (cf. the cognate series "Nucleotides" [1]). One reason for the selection of the benzyl group as a protection for phosphoric hydroxyl groups is the versatility of its reactions. Three main methods have been available hitherto for breaking the benzyl-oxygen link, namely, hydrogenolysis,[2] acidic hydrolysis,[3] and nucleophilic displacement.[4] A fourth method was discovered by Dr. A. S. Curry [5] during a repetition of the synthesis of adenosine-5′ triphosphate described by Baddiley, Michelson, and Todd.[6] Paper chromatography of the intermediates revealed that they had suffered

* Part XIII, *J.*, 1956, 1231.

[1] Brown, Todd, and Varadarajan, *J.*, 1956, 2388; and preceding papers.
[2] Zervas, *Naturwiss.*, 1939, **27**, 317; Atherton, Openshaw, and Todd, *J.*, 1945, 382.
[3] Baddiley and Todd, *J.*, 1947, 648; Elmore and Todd, *J.*, 1952, 3681.
[4] Baddiley, Clark, Michalski, and Todd, *J.*, 1949, 815; Clark and Todd, *J.*, 1950, 2023, 2031.
[5] Curry, Thesis, Cambridge, 1952.
[6] Baddiley, Michelson, and Todd, *J.*, 1949, 582.

extensive debenzylation and Dr. Curry's preliminary experiments, for information about which we are indebted to him, showed that this was caused by the phenolic solvents used. This paper records a study of the reaction as a preliminary to its use in synthesis. Some applications of the results have already been published.[7]

The products of reaction between benzyl diphenyl phosphate and phenol at 51° were diphenyl hydrogen phosphate, a little benzyl phenyl ether, and a mixture of *p*- and *o*-benzylphenol (ratio 1·22 : 1). As the ether proved to be stable under the reaction conditions, the principal course of reaction was clearly :

$$HOPh + (CH_2Ph{\cdot}O)PO(OPh)_2 \longrightarrow HO{\cdot}C_6H_4{\cdot}CH_2Ph + HO{\cdot}PO(OPh)_2$$

The progress of this solvolysis could be followed by titration with aqueous sodium hydroxide and methyl-orange in presence of carbon tetrachloride, since diphenyl hydrogen phosphate was found to remain unesterified in phenol during four days at 51°. The amount of change in a given time was almost independent of the initial concentration of benzyl ester, as required by first-order kinetics. Autocatalysis was, however, apparent from the moderate acceleration caused by the addition of diphenyl phosphate. Toluene-*p*-sulphonic acid was, of course, a much more efficient catalyst, and convenient rates were obtained by using it at 20° in *m*-cresol instead of at 51° in phenol. Under these conditions, when the autocatalysis was masked, the velocity of reaction was proportional to the concentrations of benzyl ester and of added acid. Hydrogen chloride was also an effective catalyst with a constant about twice that of toluene-*p*-sulphonic acid. The ratio of *p*- to *o*-benzylphenol was lower (0·83 : 1) when the reaction in phenol at 51° was catalysed by toluene-*p*-sulphonic acid than when it was uncatalysed. On the other hand, the solvolysis of benzyl bromide by phenol at 51°, whether in the presence of added acid or not, gave much more of the *p*-isomer (ratios 2·50 : 1, 2·59 : 1, respectively). A closer analogy with the diphenyl phosphate reaction is provided by the work of Földi,[8] who isolated 25% of *p*- and 30% of *o*-benzylphenol from the solvolysis of benzyl benzenesulphonate in phenol at 150°; traces of benzyl phenyl ether were produced in this reaction also.

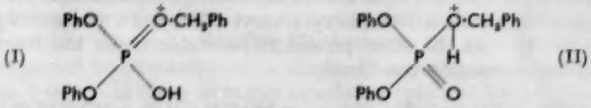
The rôle of the phenol is complicated since it acts both as hydroxylic solvent of the phosphate fragment and as acceptor of the benzyl group. The rate of reaction is approximately the same in *m*-methoxyphenol as in phenol, but is considerably less in the cresols and in *p*-chlorophenol. No reaction could be detected in anisole even when much acid was added. Anisole is doubtless much less efficient than phenol both as a solvent and as a nucleophilic reagent : its bromination in acetic acid is slower by two powers of ten.[9] Dr. Curry's observation [5] that the reaction is inhibited by relatively small quantities of methyl cyanide has been confirmed. Methanol has the same effect. The similar inhibition by dioxan of the reaction between phenol and *tert.*-butyl chloride has been attributed [10] to the formation of hydrogen-bond complexes and consequent removal of the phenol from the reaction; an alternative explanation in the present instance is competition between the diluent and the benzyl phosphate for the acid catalyst.

The results of our experiments, which were largely aimed at practical improvement of the technique of debenzylation, agree with the following, admittedly speculative, ideas about the mechanisms of the reactions. Solvolysis can proceed through a slow ionisation producing a benzyl cation, which is accepted by phenol mainly at its *para*-position. When acid has been liberated by solvolysis or acid has been deliberately added, the mesomeric cation (I) and perhaps the cation (II) can be formed and undergo bimolecular substitution at the *ortho*- and, to a smaller extent, the *para*-position of the phenol.

Dibenzyl phenyl phosphate is more similar than benzyl diphenyl phosphate to the benzylated intermediates normally encountered in synthetical work, and its solvolysis by phenol was therefore examined. Phenyl dihydrogen phosphate was isolated as its mono-*cyclo*hexylammonium salt in good yield, but the reaction was considerably slower than in the earlier example (19·5% complete in 1 hr. instead of 41%); the solvolysis of tribenzyl

[7] Christie, Kenner, and Todd, *J.*, 1954, 46; Kenner, Todd, Webb, and Weymouth, *ibid.*, p. 2288.
[8] Földi, *Ber.*, 1928, **61**, 1609.
[9] Robertson, de la Mare, and Swedlund, *J.*, 1953, 782.
[10] Hart, Cassis, and Bordeaux, *J. Amer. Chem. Soc.*, 1954, **76**, 1639.

phosphate was slower still (8%). Evidently the reaction is accelerated by the withdrawal of electrons from the phosphate group by the aryl nucleus and the consequent increase in polarity of the benzyl–oxygen link. Other differences between the behaviours of phenyl and benzyl esters arising from the same cause have already been noted in Part X.[11] On



the other hand the solvolysis by *m*-cresol containing hydrogen chloride proceeded at about the same speed in all three cases. This difference between the reactions with and without added acid is reasonably explicable if the main mechanism of the first class is ionisation to a benzyl cation whilst that of the second class is nucleophilic attack on an ion such as (I) or (II). The above results refer to only the first step of a multiple debenzylation since titration to methyl-orange detects only primary phosphoric acid groups. The sum of the primary and secondary acidic groups can be determined by potentiometric titration in aqueous acetone. By this method it was possible to compare the acid-catalysed solvolysis by *m*-cresol of benzyl phenyl hydrogen phosphate with that of dibenzyl phenyl phosphate. This showed that the second step of a double debenzylation is appreciably slower than the first.

The removal of benzyl groups from esters of pyrophosphoric acid is, if anything, of greater practical importance than the operation with orthophosphates. The solvolysis of tetrabenzyl pyrophosphate was much faster even than that of benzyl diphenyl phosphate whether the reaction studied was simple solvolysis by phenol at 51° (complete in 1 hr.) or the hydrogen chloride-catalysed reaction in *m*-cresol (1·59 equivalents of acid liberated under conditions which produced only 0·22 equivalent in the example studied earlier). The way in which this difference can be exploited for the synthesis of pyrophosphates has been pointed out elsewhere.[12] Only the first two stages of the tetradebenzylation could be detected by either of the titration techniques, but the last three stages were studied by paper chromatography, with one of the very efficient systems described by Ebel,[13] and colorimetric estimation of the phosphorus content of different portions of the paper. The results show that the final stages of debenzylation were still rapid but that the full yield of pyrophosphoric acid was never obtained because considerable breakdown to orthophosphoric acid occurred. This was evidently not caused by the cresol, since there was no sign on the chromatograms of *m*-tolyl dihydrogen phosphate and no loss of phosphate to unaccounted sources. Moreover the breakdown eventually ceased and must therefore have been caused by traces of water. The chromatograms of the later samples showed the presence of triphosphoric and, probably, tetraphosphoric acid in increasing and then constant amounts. These results are easily explained by the hypothesis that reactions of the following type took place :

$$2H_4P_2O_7 \rightleftharpoons H_5P_3O_{10} + H_3PO_4$$
$$H_4P_2O_7 + H_5P_3O_{10} \rightleftharpoons H_6P_4O_{13} + H_3PO_4$$
$$2H_5P_3O_{10} \rightleftharpoons H_6P_4O_{13} + H_4P_2O_7$$

It should be remarked that these reactions were slower than the hydrolysis, which in turn was slower than the debenzylation. The phenolic debenzylation method is therefore likely to be useful, particularly if water can be excluded, provided that the reaction is not prolonged excessively.

It would have been interesting to examine the phenolic debenzylation of pentabenzyl triphosphate, but we were unable to prepare a satisfactory sample of this presumably unstable substance from dibenzyl phosphorochloridate and triethylammonium tribenzyl pyrophosphate.

[11] Corby, Kenner, and Todd, *J.*, 1952, 1236.
[12] Christie, Kenner, and Todd, *J.*, 1954, 47.
[13] Ebel, *Bull. Soc. chim. France*, 1953, 991.

Experimental

M. p.s are corrected.

4-Benzyl-2-p-nitrophenylazophenol.—A 0·32N-solution of *p*-nitrobenzenediazonium chloride (15 c.c.; prepared according to Saunders [14]) was added slowly to a stirred solution of *p*-benzylphenol [15] (0·505 g.) in 0·1N-sodium hydroxide (5 c.c.). A portion of the *azo-compound*, which was precipitated by acidification, was purified by chromatography in benzene on alumina and crystallised from aqueous ethanol in orange-red crystals, m. p. 173—174°, $\varepsilon_{max.}$ 21,180 at 340 mμ in C_6H_6 (Found, in material dried at 90°: C, 69·1; H, 4·7; N, 12·8. $C_{19}H_{15}O_3N_3$ requires C, 68·5; H, 4·5; N, 12·6%).

Coupling of o-Benzylphenol with Diazotised p-Nitroaniline.—Dilute hydrochloric acid was added to *o*-benzylphenol [16] (0·05 g.) in sodium hydroxide solution until a very slight turbidity was produced. The diazonium solution (1 c.c.; as above) was then added and followed by acid to precipitate a mixture of dyes, which was separated by chromatography in benzene on alumina into a rapidly moving purple band and a slow pink band. The latter consisted of *2-benzyl-4-p-nitrophenylazophenol* which, eluted by chloroform and crystallised from aqueous ethanol, had m. p. 150—152°, $\varepsilon_{max.}$ 22,900 at 376—378 mμ in C_6H_6 (Found, in material dried at 90°: C, 68·4; H, 4·6; N, 12·7%). When a greater quantity (4 c.c.) of the diazonium solution was used together with sufficient sodium hydroxide to maintain the alkalinity, the purple band was more intense and it yielded *2-benzyl-4 : 6-bis-p-nitrophenylazophenol* as a brown amorphous solid, m. p. 214—215°, $\varepsilon_{max.}$ 41,000 at 366—370 mμ (Found, in material dried at 90°: C, 62·5; H, 3·9; N, 17·5. $C_{25}H_{18}O_5N_6$ requires C, 62·2; H, 3·8; N, 17·4%).

Determination of p- and o-Benzylphenol in a Mixture with Phenol.—Phenol (0·153 g.), *p*-benzylphenol (0·0617 g.), and *o*-benzylphenol (0·0526 g.) were dissolved in ethanol (25·0 c.c.). A portion (5·0 c.c.) of this solution was stirred with water (5 c.c.) and magnesium oxide (2 g.; "AnalaR") in an ice-cooled flask. *p*-Nitrobenzenediazonium chloride solution (5 c.c.; as above) was slowly added, followed, 10 min. later, by concentrated hydrochloric acid (10 c.c.). Immediate addition of water (200 c.c.) precipitated an amorphous brown powder, which was collected, washed with dilute hydrochloric acid and water, and dried (0·2438 g.). A portion (5·0 c.c.) of a solution of this powder (0·0215 g.) in benzene (100·0 c.c.) was concentrated to about 2 c.c. and applied to a column (12 × 1 cm.) of alumina (Spence "H," deactivated by 2% of water). Washing the column with benzene eluted 4-benzyl-2-*p*-nitrophenylazophenol [50 c.c. of solution, optical density in 1 cm. cell (*D*) 0·123 at 337 mμ], followed by 2-benzyl-4 : 6-bis-*p*-nitrophenylazophenol (81 c.c., *D* 0·100 at 370 mμ). Ether then removed the 2-benzyl-4-*p*-nitrophenylazophenol, which was recovered by evaporation and redissolved in benzene (5 c.c., *D* 0·171 at 378 mμ). The dyes formed from the phenol remained strongly adsorbed at the top of the column. Calculation, with the previously determined extinction coefficients, shows that the eluted dyes correspond to 0·0607 g. of *p*- and 0·0491 g. of *o*-benzylphenol, 98 and 93% respectively of the amounts used.

Stability of Benzylphenols in Phenol.—A solution of *p*-benzylphenol (0·210 g.; m. p. 82—83°) in phenol (5 c.c.) was kept at 51° during 96 hr. The *p*-benzylphenol was recovered unchanged (m. p. 82—83°) on sublimation of the phenol at 20°/10^{-2} mm. until the residue reached constant weight (0·213 g.). *o*-Benzylphenol (0·192 g.; m. p. 50—52°) was treated in the same way and recovered (0·192 g.; m. p. 49—52°).

A solution of *p*-benzylphenol (0·245 g.) in phenol (5 c.c.) containing toluene-*p*-sulphonic acid (0·0116N) was kept at 51° during 48 hr. and then diluted with benzene (15 c.c.) before extraction with saturated sodium hydrogen carbonate solution (2 × 5 c.c.) and water (5 c.c.). The benzene solution was frozen and evaporated to constant weight (0·248 g.); the m. p. of the residue was 82—83°. *o*-Benzylphenol (m. p. 48—52°) was likewise recovered in quantitative yield.

Stability of Benzyl Phenyl Ether in Phenol.—A solution of benzyl phenyl ether (1 g.; m. p. 39°) in phenol (10 c.c.) was kept at 51° during 22 hr. and then diluted with carbon tetrachloride (35 c.c.) before three extractions with N-sodium hydroxide. Evaporation of the dried (Na_2SO_4) carbon tetrachloride, finally at 80°/2 mm., left unchanged benzyl phenyl ether (0·986 g.; m. p. 39° after crystallisation from ethanol).

A mixture of benzyl phenyl ether (1·018 g.), diphenyl hydrogen phosphate (0·740 g.), and

[14] Saunders, "Aromatic Diazo Compounds," Arnold, London, 1949, 2nd edn., p. 6.
[15] Short and Stewart, *J.*, 1929, 553.
[16] Claisen, *Annalen*, 1925, **442**, 238.

phenol (10 c.c.) yielded 0·920 g. of unchanged ether after being kept for 17 hr. at 51°. A mixture of the ether (1·058 g.), toluene-*p*-sulphonic acid (0·693 g.), and phenol (10 c.c.) gave 0·672 g. of unchanged ether after 2 hr. at 51°.

Benzyl Diphenyl Phosphate.—Diphenyl phosphorochloridate (50 g.) was added during 2 hr. to pyridine (25 g.) and benzyl alcohol (20·1 g.), stirred at 0°. After 4 hr. further, the neutral product was extracted by ether (2 × 100 c.c.) after addition of water (100 c.c.) and was washed with N-sulphuric acid, N-sodium hydrogen carbonate solution, and water. The oil remaining after evaporation of the dried ether crystallised : recrystallisation from light petroleum (b. p. 40—60°) afforded *benzyl diphenyl phosphate*, m. p. 48° (54·5 g., 86%) (Found : C, 67·0; H, 5·3. $C_{19}H_{17}O_4P$ requires C, 67·1; H, 5·0%). Preparation of the oil has been recorded.[17]

Solvolysis of Benzyl Diphenyl Phosphate.—(1) *Acidic product.* A solution of the ester (0·615 g.) in phenol (10 c.c.) was kept at 51° during 72 hr. before dilution with benzene (25 c.c.). The solution was extracted with saturated sodium hydrogen carbonate solution (5 × 4 c.c.). The aqueous extracts were passed through a column (10 × 1 cm.) of Zeo-Karb 215 cation-exchange resin (hydrogen-ion form), which was washed with water until the eluate was neutral. *cyclo*-Hexylamine (0·4 c.c.) was added to the combined eluate, which was then evaporated to dryness. Addition of light petroleum (b. p. 40—60°) to the acetone solution of the residue precipitated crystalline *cyclo*hexylammonium diphenyl phosphate (0·510 g. 86%), m. p. 200° undepressed by an authentic sample.[20]

(2) *Neutral product.* A solution of benzyl diphenyl phosphate (0·315 g.) in phenol (5 c.c.) was kept at 51° during 70 hr. and then diluted with carbon tetrachloride (30 c.c.). After extraction with 1·5N-sodium hydroxide (5 × 40 c.c.) and water (3 × 40 c.c.), the solvent was evaporated. Two crystallisations of the residue from light petroleum afforded crude benzyl phenyl ether (0·01 g., 6%), m. p. 32—34° undepressed by an authentic specimen of m. p. 39°.

(3) *Phenolic product.* (*a*) Qualitative tests. The carbon tetrachloride solution of the solvolysis products, obtained as in (2) above, was extracted first with sodium hydrogen carbonate solution and then with sodium hydroxide solution, from which the phenols were recovered by acidification and ether-extraction. When an ethanolic solution of 2 : 6-dichloroquinone chloroimine was added to a dilute alkaline solution of this material, a deep blue colour was produced and this became bluish-pink on dilution. *o*-Benzylphenol behaved in the same way, but *p*-benzylphenol gave a brownish-blue colour, fading to slate-grey and becoming grey on dilution.[18] The dyes obtained by coupling the phenolic product with diazotised sulphanilic acid were dissolved in ethanol and applied to Whatman No. 3 paper, previously soaked in 1% sodium hydrogen carbonate solution and dried.[19] Ascending development of the paper with butan-1-ol–ethanol (50 : 13 v/v), saturated with water, gave a chromatogram pattern similar to that from a mixture of equal weights of *p*- and *o*-benzylphenol and phenol. *p*-Benzylphenol alone gave a strong pink spot (R_F 0·72), whereas *o*-benzylphenol gave a strong orange spot (R_F 0·58) together with three faint spots (orange R_F 0·48, orange R_F 0·42, mauve R_F 0·36). Phenol gave a yellow spot (R_F 0·32).

(*b*) Quantitative analysis. A solution of benzyl diphenyl phosphate (0·615 g.) in phenol (3 c.c.) was kept at 51° during 72 hr. and then diluted with benzene (25 c.c.), which was extracted with saturated sodium hydrogen carbonate solution (5 × 4 c.c.). The residue from evaporation of the benzene and sublimation at 10^{-3} mm. (10 hr.) of the phenol was dissolved in ethanol (10·0 c.c.). A portion (2·0 c.c.) of this solution was converted, as previously described, into the *p*-nitrophenylazo-derivatives, which were separated chromatographically and estimated photometrically in the standard fashion. They corresponded to 0·156 g. of *p*- and 0·129 g. of *o*-benzylphenol, making a total yield of 85·5% whereas the extent of debenzylation, as determined by titration, was 94%.

From a mixture of the ester (0·388 g.) and phenol (3 c.c.) containing toluene-*p*-sulphonic acid (0·1N), which had been kept for 3 hr. at 51°, there were likewise obtained dyes corresponding to 0·0819 g. of *p*- and 0·0985 g. of *o*-benzylphenol (total yield 86%).

Solvolysis of Benzyl Bromide.—A mixture of benzyl bromide (0·719 g.) and phenol (3 c.c.) was kept at 51° during 48 hr., hydrogen bromide being released at intervals. The yellowish-brown solution, treated as in the preceding experiment, gave dyes corresponding to 0·524 g. of *p*- and 0·2025 g. of *o*-benzylphenol (total yield 94%).

A solution of benzyl bromide (0·719 g.) in phenol (3 c.c.) containing toluene-*p*-sulphonic acid

[17] Lora Tamayo and Gregorio Ramon, *Anal. Fis. Quim.*, 1949, **45**, *B*, 1123.
[18] Cf. Gibbs, *J. Biol. Chem.*, 1927, **72**, 649.
[19] Cf. Hossfeld, *J. Amer. Chem. Soc.*, 1951, **73**, 852.
[20] Lecocq and Todd, *J.*, 1954, 2384.

(0·142N) was kept at 51° during 5 hr.; it gave dyes corresponding to 0·497 g. of *p*- and 0·199 g. of *o*-benzylphenol (total yield 90%).

Solvolysis of Dibenzyl Phenyl Phosphate.—The acidic product was recovered from a mixture of the ester (0·0816 g.) and phenol (3 c.c.), which had been kept for 68 hr. at 51°, in the same way as from benzyl diphenyl phosphate. *cyclo*Hexylammonium phenyl hydrogen phosphate (0·052 g., 82%), m. p. 211° undepressed by an authentic specimen,[21] was precipitated from aqueous solution by addition of acetone.

Kinetics of the Solvolysis of Benzyl Diphenyl Phosphate.—(1) *At 51°.* The solution of the ester in phenol (20·0 c.c.) was contained by a 50 c.c. flask with a water-jacketed neck (10 × 1 cm.). During the run cold water was circulated in the jacket, but, immediately before each sample was taken, hot water was circulated in order to melt the sublimed phenol and return it to the flask. The sample (1 or 2 c.c.) was run into cold water (about 5 c.c.) containing carbon tetrachloride (about 5 c.c.) and 2 drops of methyl-orange, and was titrated with 0·0648N-sodium hydroxide. In calculations of the extent of reaction the change in volume caused by dissolution of the ester in phenol was neglected.

(*a*) Order of the reaction with respect to the ester. In a series of runs the percentage change in a given time was found to be independent of the initial ester concentration, as required by first-order kinetics, *e.g.*, at initial ester concentrations of 0·257 and 0·086M the percentage changes were respectively 22·2 and 21·0 at 30 min., 41·4 and 41·0 at 60 min., 59·2 and 58·4 at 90 min.

(*b*) Autocatalysis and the effect of diphenyl hydrogen phosphate. A run with an initial ester concentration of 0·246M was made and then repeated with added diphenyl hydrogen phosphate (0·119M). Results are tabulated.

Time (min.)	5	10	15	20	30	45	60	90	120
Change (%) (without acid) ...	4·08	7·28	11·40	14·98	22·18	32·44	41·46	59·20	70·40
Change (%) (acid added)	2·74	10·10	15·10	20·48	39·60	44·80	55·60	71·60	82·20

(*c*) Catalysis by toluene-*p*-sulphonic acid. The reaction was complete in less than 5 min. when a run was made with initial concentrations of 0·257M-ester and 0·137M-acid, and complete in 15 min. with concentrations of 0·514 and 0·023M respectively. A run with 0·275M-ester and 0·00639M-acid was 78·8% complete in 30 min.

(*d*) Comparison of different phenols. In one series of runs with 0·257M-ester the change in 30 min. was 26·2% in *m*-methoxyphenol, 22·2% in phenol, and 10·4% in *p*-chlorophenol. In a second series with 0·275M-ester, toluene-*p*-sulphonic acid was added at the concentration shown in parentheses and the change in 30 min. was 78·8% (0·00639) in phenol, 78·0% (0·00620) in *m*-methoxyphenol, 53·2% (0·00642) in *m*-cresol, 32·5% (0·00639) in *p*-cresol, 23·2% (0·00564) in *o*-cresol and 0·0% (0·0308) in anisole.

(*e*) Inhibition of the solvolysis by methyl cyanide and methanol. The reaction in phenol without added catalyst or inhibitor was 22% complete in 30 min., but was only 16·4, 13·4, and 5·1% complete in 30 min. when methyl cyanide was added in concentrations of 0·936, 1·79, and 3·75M respectively to 0·245, 0·239, and 0·206M-solutions of the ester. A mixture which was 2·23M in methanol and 0·234M in ester showed 10·6% complete reaction in 30 min.

(2) *At 20° in m-cresol.* The procedure was the same as described in (1) except that a simple stoppered flask was used.

(*a*) Order of catalysis by toluene-*p*-sulphonic acid. Results are tabulated, the percentage change being $100x/a$, and $k = \{2{\cdot}303 \log [a/(a - x)]\}/15b$. The results are reasonably com-

Molarity (*a*) of ester	0·119	0·135	0·150	0·178	0·197	0·237
Molarity (*b*) of acid	0·0392	0·0308	0·0479	0·0366	0·0528	0·0857
Change (%) in 15 min.	16·9	14·5	18·6	14·5	19·8	28·8
k	0·314	0·340	0·288	0·286	0·278	0·264

patible with the assumption that velocity = k[Ester][Acid] as shown by the values of k (mean 0·295 min.$^{-1}$ mol.$^{-2}$ l.) calculated on this assumption. An alternative way of deriving k from the complete results of a single run is to plot time against log $[a/(a - x)]$ and then use $k = 2{\cdot}303/(b, \text{slope})$; the run with 0·197M-ester gave 0·282 for k in this way.

(*b*) Catalysis by hydrogen chloride. In this case a straight-line graph of time against log $[a/(a - x)]$ was not obtained because appreciable amounts of hydrogen chloride were lost from

[21] Baddiley, Clark, Michalski, and Todd, *J.*, 1949, 818.

the bulk of solution during the withdrawal of samples. A control experiment showed that 10 c.c. of 0·0452M-hydrogen chloride in *m*-cresol lost 8·3% of its acidity during 3 minutes' exposure to air. The initial slopes of the graphs were therefore used and gave a mean k value of 0·575. In a typical run with 0·141M-ester and 0·069M-acid the change was 46·9% in 15 min. and 62·9% in 30 min.

(*c*) Catalysis by trichloro- and trifluoro-acetic acid. Reaction was 53·8% complete in 20 hr. when 0·131M-trichloroacetic acid was used with 0·120M-ester, and 78·5% complete in 17 hr. when 0·0556M-trifluoroacetic acid was used with 0·131M-ester.

Kinetics of the Solvolysis of Dibenzyl Phenyl Phosphate, Benzyl Phenyl Hydrogen Phosphate, Tribenzyl Phosphate, and Tetrabenzyl Pyrophosphate.—(1) *Followed by indicator titration.* (*a*) In phenol at 51° without added acid. Solvolysis of dibenzyl phenyl phosphate (0·136M) produced titratable acid in the following amounts (expressed as mols. % of the ester concentration), 8·3% in 30 min., 19·5% in 60 min., 50·6% in 150 min. Tribenzyl phosphate (0·131M) gave 8% in 1 hr., 20·2% in 3 hr., 92·5% in 68 hr. Tetrabenzyl pyrophosphate (0·084M) gave 160% in 30 min., 190% in 60 min., 190% in 180 min.

(*b*) At 20° in *m*-cresol containing hydrogen chloride. Solvolysis of dibenzyl phenyl phosphate (0·149M) in *m*-cresol, 0·0269M in hydrogen chloride, produced 43·6% of acid in 30 min., 73·7% in 17 hr. Tribenzyl phosphate (0·158M) in 0·0328M-acid gave 44·7% in 30 min., 66% in 79 hr. Tetrabenzyl pyrophosphate (0·090M) in 0·042M-acid gave 157% in 30 min. and 171% in 17 hr.

(2) *Followed by potentiometric titration.* The samples were run into water (about 10 c.c.) and sufficient acetone (about 5 c.c.) to maintain homogeneity during the titration. This was conducted with a glass electrode–calomel electrode pH-meter, the nominal pH being read as each small portion of alkali was added. A plot of ΔpH/Δvol. against vol. of alkali added showed a series of peaks corresponding to the different acidic species. The position of the last peak was taken as giving the total acid present except for the tertiary dissociation of orthophosphoric acid and the two secondary dissociations of pyrophosphoric acid. All the runs were made in *m*-cresol at 20°. Dibenzyl phenyl phosphate (0·129M) together with 0·0309M-hydrogen chloride gave 118 mols.% of acid in 1 hr. and 179% in 2 hr., whereas benzyl phenyl hydrogen phosphate (0·128M) with 0·0309M-acid gave 29·4% in 1 hr. and 75% in 7 hr. Tetrabenzyl pyrophosphate (0·0804M) with 0·0336M-acid gave 172% in 1 hr.; a final value of 185% was obtained when the mixture was heated at 55° for 1 hr. after 13 hr. at 20°.

Chromatographic Investigation of the Degradation of Tetrabenzyl Pyrophosphate by m-*Cresol and Toluene*-p-*sulphonic Acid.*—Freshly distilled *m*-cresol (5 c.c.) and dry toluene-*p*-sulphonic acid (0·0515 g.) were placed in a test-tube, fitted by a ground-glass joint with an adaptor which had a side-arm and a sampling-tube reaching to the bottom of the test-tube and closed by a tap. The cresol was boiled until vapour issued freely from the side-arm, which was closed with a calcium chloride drying-tube before the solution was allowed to cool to room temperature (24°). While the adaptor was momentarily removed, tetrabenzyl pyrophosphate (0·199 g.) was added and then dissolved by shaking of the tube. Samples of about 0·1 c.c. were blown through the tap by applying air pressure to the drying-tube. A micro-syringe was used to apply 0·03 c.c. of each sample along a 10 cm. line at the base of a strip of Whatman No. 1 paper, which had been dried after being washed with N-hydrochloric acid and water. Development of the ascending paper chromatogram in propan-2-ol (75 c.c.)–water (25 c.c.)–trichloroacetic acid (5 g.)–ammonia solution (0·25 c.c.; d 0·88) was begun immediately and was continued for 12—24 hr. The paper was then dried and the phosphorus-containing bands were located by the molybdate reagent.[22] Six different bands were obtained from the various samples and four of them were identified by direct comparison with known compounds: mean R_F 0·40 triphosphoric acid, 0·54 pyrophosphoric acid, 0·66 orthophosphoric acid, 0·85 P^1P^2-dibenzyl dihydrogen phosphate. The two remaining bands were believed to contain tetraphosphoric acid (mean R_F 0·27) and benzyl trihydrogen phosphate (mean R_F 0·73). Each band was cut out and the strips of paper were digested with hot 60% perchloric acid (2·2 c.c.) until a colourless solution resulted. The phosphate content of this was then estimated by Allen's method,[23] allowance being made for the " blank " given by the same area of paper which had been irrigated with the solvent but had not been treated with phosphate. The total phosphorus content (158 μg.) of 0·03 c.c. of the cresol solution was estimated directly, with 0·03 c.c. of cresol for the " blank "; determination of the phosphorus content of a longitudinal, instead of a lateral, strip of paper which had been

[22] Hanes and Isherwood, *Nature*, 1949, **164**, 1107.
[23] Allen, *Biochem. J.*, 1940, **34**, 858.

developed gave a similar value (156 μg.). Hence the cresol solution was initially 0·085M-tetrabenzyl pyrophosphate and 0·069M-toluene-*p*-sulphonic acid. The percentages of the total phosphorus content found in the various bands are tabulated.

Time of sampling (hr.)	½	1	2	4	6	9	12
Tetraphosphoric acid	—	—	2·8	2·3	3·1	2·8	2·5
Triphosphoric acid	—	4·5	9·5	6·6	15	15·8	14·6
Pyrophosphoric acid	60	62	51	34	29	31	29
Orthophosphoric acid	6·8	22	35	44	42	44	45
Monobenzyl pyrophosphate	14·5	1·9	—	—	—	—	—
Dibenzyl pyrophosphate	4·6	1·5	—	—	—	—	—
Phosphorus accounted for (%)	87	92	98	87	89	94	92

We thank Sir Alexander Todd, F.R.S., for his interest, the Department of Scientific and Industrial Research for a Maintenance Grant (to J. M.), and the Rockefeller Foundation for their support.

UNIVERSITY CHEMICAL LABORATORY, CAMBRIDGE. [*Received, September 21st*, 1955.]

---

683. *Some Aspects of the System Uranium Trioxide–Water.*

By J. K. DAWSON, E. WAIT, K. ALCOCK, and D. R. CHILTON.

Uranium trioxide in contact with water at about 180° gives an orthorhombic hydrate, $UO_3,0{\cdot}8H_2O$, with the cell dimensions $a = 10{\cdot}23 \pm 0{\cdot}01$, $b = 6{\cdot}89 \pm 0{\cdot}01$, $c = 4{\cdot}28 \pm 0{\cdot}01$ Å. These dimensions appear to vary slightly with deviation of the water content from 0·8 mole per uranium atom. Between 200° and 280° another phase appears, $UO_3,1{\cdot}0H_2O$, also orthorhombic with cell dimensions $a = 5{\cdot}638 \pm 0{\cdot}005$, $b = 6{\cdot}273 \pm 0{\cdot}005$, $c = 9{\cdot}925 \pm 0{\cdot}005$ Å, space-group *Pbca*. The hemihydrate, $UO_3,0{\cdot}5H_2O$, is stable in water above 280°. A further phase, possibly due to a relatively high pH and probably triclinic, was observed when the uranium trioxide was heated in water at 230° in contact with glass.

Some of the properties of these hydrates are described, together with observations on the preparation of pure anhydrous uranium trioxide from uranyl nitrate.

PREVIOUS investigations on the hydrated oxides of uranium indicated that the trioxide is stable in water, up to high temperatures, and that over the range 70—300° (approx.) it forms a monohydrate.[1] The system is quite complex, however, and Katz and Rabinowitz quoted the following four crystalline modifications observed by D. T. Vier: (i) α-UO_3,H_2O, large six-sided orthorhombic basal tablets; (ii) β-UO_3,H_2O, small orthorhombic prismatic tablets with slightly larger unit cell than the α-form; (iii) γ-UO_3,H_2O, six-sided columnar crystals, with *X*-ray diffraction pattern similar to that of the α- and the β-form, but perhaps belonging to a different system: contains <0·9 mole of H_2O per uranium atom; (iv) δ-UO_3,H_2O, triclinic, giving a complex *X*-ray diffraction pattern. The last form may be due to impurities.

Very few details were given of the preparation and the relations between these various forms, and the present investigation was undertaken to obtain more extensive information in the range 180—320°. The particular form of UO_3,H_2O obtained may be sensitive to the presence of traces of impurities, such as the soluble uranyl ion, and so some observations are made also on the preparation of uranium trioxide free from all contaminants down to a level of a few parts per million.

EXPERIMENTAL

The thermogravimetric curves were obtained by use of a quartz helix balance. A sample (about 100 mg.) was suspended in a platinum boat on the end of a 35-cm. extension fibre from the lower end of the helix. The temperature of the sample was raised linearly at about 2°/min.

[1] "The Chemistry of Uranium, Part I," National Nuclear Energy Series, VIII—5, edited by Katz and Rabinowitz, McGraw-Hill Book Co., New York, 1951, pp. 281—283.

by feeding a furnace surrounding the platinum boat from a variable transformer which had a spindle turned by a motor-actuated cam.[2] Weight changes caused the vertical movement of an index fibre at the lower end of the helix and this was measured by a cathetometer; the sensitivity of the system was 0·85 mm./mg. The helix was surrounded by a glass tube which was connected by a ground joint to a quartz tube surrounding the platinum boat, and the system was evacuated to 0·1 mm. for a short time before each experiment in order to ensure the absence of moisture on the helix.

Preliminary experiments showed that all forms of hydrated uranium trioxide were converted into U_3O_8 at about 700° after 1 hr. in air. This was used as the basis for the determinations of water content, any change in weight between the sample and U_3O_8, after allowance for the decrease of oxygen content $UO_3 \longrightarrow UO_{2\cdot67}$, being attributed to loss of water. Before analysis, samples of hydrate were normally dried on a sintered-glass disc at room temperature in a current of air for 5 hr. The validity of the method was checked by separate experiments. For instance, 1·457 g. of orthorhombic II hydrate were heated in a nitrogen stream to 450° for 90 min. and the nitrogen was subsequently passed through a weighed tube containing magnesium perchlorate. The increase in weight of the latter was 0·086 g.; and the water content corresponds to $UO_3,1{\cdot}00H_2O$. The loss of weight of the uranium trioxide agreed within experimental error with the gain of the magnesium perchlorate.

A similar experiment with a sample consisting almost entirely of orthorhombic I hydrate showed that 0·993 g. lost 50·1 mg. of water, corresponding to a formula of $UO_3,0{\cdot}85H_2O$. The thermogravimetric curves of both hydrates also supported these figures.

At the beginning of this investigation no steel autoclaves were available and so attempts were made to bring about the reaction of uranium trioxide with high-temperature water in glass tubes of 2 mm. wall thickness and about 15 ml. capacity. In order to prevent contamination of the product with silica, some of the experiments were performed with the uranium trioxide contained in a platinum tube inside the glass tube. Tubes (20 mm. diam.) would usually withstand the steam pressures at these temperatures provided that care was taken to ensure a symmetrical seal. The tubes were heated in a furnace fitted with a metal safety screen, and in the first experiments the slurries were agitated by continuously rotating the tubes end-over-end; later experiments were performed without agitation in order to grow more perfect crystals.

Subsequently the slurries were heated in stainless-steel autoclaves which could be agitated by rocking if desired. Usually 2 g. of uranium trioxide were heated with 80 ml. of water, but occasionally the scale was increased to 50 g. of oxide.

The product of each experiment was examined visually under a projection microscope at × 1000 magnification. *X*-Ray diffraction photographs were obtained on the powders by use of a Guinier-type focusing camera with negligible background.[3] Cu-$K\alpha$ radiation was used in all cases; wavelengths were taken as $K\alpha_1 = 1{\cdot}54051$ Å and $K\alpha_2 = 1{\cdot}54433$ Å. Samples were approximately five microns thick. In cases where suitable crystals were available, single-crystal Weissenberg methods were also used to supplement the powder data. A micromanipulator technique was necessary for mounting the very small crystals and this will be described elsewhere.

Results and Discussion

The following five crystallographically distinct hydrate phases were obtained during the course of this investigation and they are described here in order to aid the discussion of results: (i) $UO_3,2H_2O$, obtained only as very small particles, by reaction of anhydrous UO_3 with water at room temperature. (ii) $UO_3,0{\cdot}8H_2O$, orthorhombic I, thin yellow rods about 10 μ long and showing straight extinction between crossed polaroids. When these were heated in air, there was a slight loss of weight up to 250°, but most of the water was not eliminated below ~300° (see Fig. 1). This phase is probably the same as Vier's γ-UO_3,H_2O (p. 3531). (iii) $UO_3,1{\cdot}0H_2O$, orthorhombic II, crystallised as orthorhombic tablets, sometimes up to 150 μ long, with symmetrical extinction between crossed polaroids. It was almost colourless under the microscope. Thermogravimetric curves showed that this hydrate had remarkable stability in air, there being no loss of weight up to at least 360°. Rapid dehydration occurred at 400°. (iv) $UO_3,?H_2O$, monoclinic, or triclinic. This phase (III) was obtained in the presence of "Pyrex" glass at 230° and was observed

[2] Ball and Adams, *J. Sci. Instr.*, 1951, **28**, 47.
[3] D'Eye, A.E.R.E. C/R—1524.

in the form of stubby triclinic prisms, about 10 μ long. Sometimes it was observed also as large flat intensely yellow plates.* (v) $UO_3.0{\cdot}5H_2O$, monoclinic, usually twinned, as short oblique-ended laths.

(a) *The Conversion of Hydrated Uranyl Nitrate into Uranium Trioxide.*—There are several routes by which trioxide may be obtained from the readily available nitrate; the two most promising appeared to be :

$$(\alpha)\ UO_2(NO_3)_2.6H_2O \xrightarrow{\text{heat}} UO_3$$

$$(\beta)\ UO_2(NO_3)_2.6H_2O \xrightarrow{+H_2O_2} UO_4.2H_2O \xrightarrow{\text{heat}} UO_3$$

The decomposition of thermally unstable organic uranyl compounds was not favoured owing to the possibility of obtaining lower oxides.[4] Thermal decomposition curves for uranyl nitrate hexahydrate are shown in Fig. 2 for ignition in air and *in vacuo*. There

FIG. 1. *Thermogravimetric curve for* $UO_3.2H_2O$.

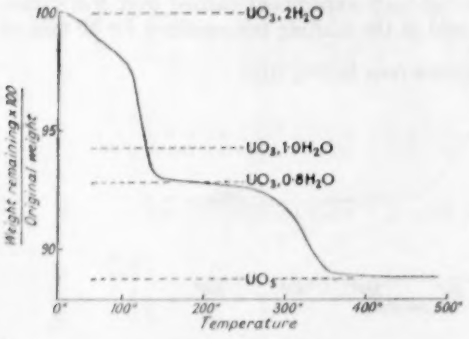
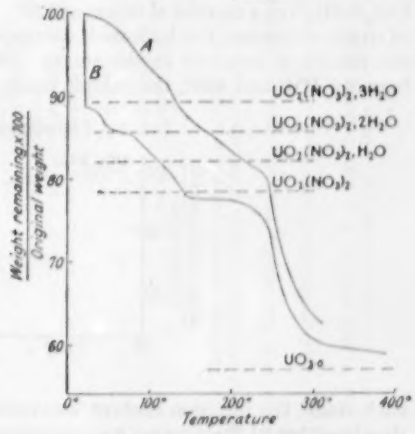


FIG. 2. *Thermogravimetric curves for uranyl nitrate hexahydrate.*



A—in air; *B*—*in vacuo*.

was only a slight difference in decomposition temperature by the two methods. The formation of pure uranium trioxide by this method is complicated, as the decomposition temperature of the nitrate is close to the stability limit in air of the oxide. Suitable temperatures quoted by earlier workers [5] have varied between 250° and 500°. Our results indicate that the temperature should be greater than 300°. According to an isobar for 10 mm. pressure of oxygen,[6] uranium trioxide begins to lose oxygen when heated above 430°. Consequently, the optimum temperature for the production of the trioxide by nitrate decomposition is about 400°. However, when this was performed in a tube furnace with a slow current of air passing over the sample, it was found that the residual nitrogen content of the oxide after 1 hour's heating was in the range 450—700 p.p.m. (*i.e.*, up to 0·28% expressed as nitrate ion) and that further heating was not effective in removing this. The amount of residual nitrogen could be reduced by recycling the material through

* *Added July 30th, 1956.*—Investigations performed on other systems since the submission of this paper indicate that the "phase III hydrate" is probably a uranyl silicate, $(UO_2)_2SiO_4.3H_2O$ or $(UO_2)_3Si_2O_7.2H_2O$. The same substance has been prepared by the action of uranyl sulphate solution at 300° on fused silica vessels (Davidge, Lock, and Wait, unpublished work) and from the reaction between uranyl fluoride solution and silica (Marshall and Secoy, personal communication). In the experiments reported above, it was presumably formed by reaction of the residual soluble uranium content of the oxides with the walls of the glass capsules.

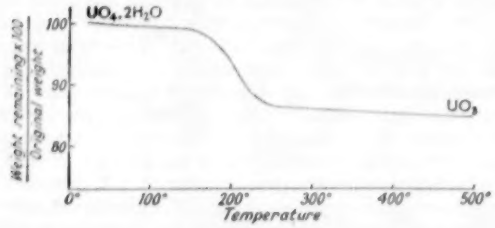
[4] "The Chemistry of Uranium," p. 317.
[5] *Ibid.*, pp. 319, 320.
[6] Biltz and Muller, *Z. anorg. Chem.*, 1927, **163**, 295.

the structural changes $UO_3,2H_2O \rightleftharpoons UO_3$ by alternate washing with water and heating at 400°. Orange-yellow uranium trioxide prepared by decomposition of uranyl nitrate or peroxide reacts rapidly with water at room temperature, producing the dihydrate with evolution of considerable heat. However, the dihydrated and the monohydrated trioxide decompose to give a red anhydrous oxide which is less reactive towards water; for reconversion into the dihydrate this requires either to be left much longer in contact with water at room temperature or to be hydrated at a rather higher temperature.

The decomposition temperature of the hydrated trioxide was considered to be 400° since this is above the stability limit of either the orthorhombic I or the orthorhombic II monohydrate phase, as determined by thermogravimetric curves, and yet below the reported stability limit of the anhydrous oxide. Fig. 1 shows the thermogravimetric curve for $UO_3,2H_2O$ which decomposes at about 140° to the orthorhombic I form, $UO_3,0{\cdot}8H_2O$, which in turn decomposes to uranium trioxide above about 360°.

An alternative method of reducing the nitrate content of the oxide involves the crystal-structure changes orthorhombic I, $UO_3,0{\cdot}8H_2O \rightleftharpoons$ anhydrous UO_3. The anhydrous oxide as prepared by direct decomposition of the nitrate is readily converted into $UO_3,0{\cdot}8H_2O$ in a current of steam at 120°. If the temperature is raised to 420° and passage of steam continued, the hydrate is decomposed to the original anhydrous phase and some of the nitrate is removed in the steam. In one such experiment carried over five cycles, between 120° and 420°, the sample being held at the limiting temperatures for 30 min. at

FIG. 3. *Thermogravimetric curve for* $UO_4,2H_2O$.



each stage, the nitrogen content was reduced from a starting value of 600 to 5 p.p.m. A disadvantage of this process was the sintering of the sample in the later stages.

(b) *Conversion of Uranium Peroxide into Uranium Trioxide.*—The preparation of pure uranium trioxide from the nitrate *via* the peroxide was also a long process. The uranium peroxide was precipitated from dilute aqueous uranyl nitrate solution by addition of dilute hydrogen peroxide; it was then centrifuged and required many washings in order to free the supernatant liquid from nitrate ion (" nitron " reagent). However, this process gave after ignition of the precipitate an anhydrous trioxide with a nitrogen content of about 30 p.p.m. After being dried overnight at 100° in air, the precipitate had the composition $UO_4,2{\cdot}0H_2O$ according to the weight change observed on igniting a sample in air to U_3O_8.

Previous results [7] on the thermal decomposition of hydrated uranium peroxide are not very consistent. A thermogravimetric curve obtained with $UO_4,2{\cdot}0H_2O$ is shown in Fig. 3. There were no plateaux between the starting material and UO_3 and it appeared that loss of oxygen and water occurred simultaneously, in agreement with Kraus's results.[8] Uranium trioxide for the hydrations was produced at about 375° (tube furnace) in a slow current of air during 1 hr.

(c) *The System* UO_3–H_2O.—The results of heating uranium trioxide with water are given in Table 1 for oxide obtained by direct thermal decomposition of the nitrate, and in Table 2 for oxide obtained by decomposition of peroxide. One of the difficulties attending this investigation was the apparent complexity of the UO_3–oxygen system, so that allowance had to be made for use as starting material of various types of uranium trioxide. A brief

[7] Summarised in " The Chemistry of Uranium," pp. 290—292.
[8] Kraus, reported in " The Chemistry of Uranium," p. 290.

TABLE 1. *Results of heating nitrate-derived* UO_3 *with water.*

	Starting material	Temp.	Time (hr.)	Container	Agitation	Soluble uranium (p.p.m.)	Soluble "N" (p.p.m.)	"N" (p.p.m.) in solid product	pH	Product: H_2O (mole per U atom)	Product: Colour	Product: X-Ray Major	Product: X-Ray Minor	Product: Optical Major	Product: Optical Minor	Product: Large yellow plates
1	UO_3 from nitrate	180°	24	Glass	+	1836	152		4·1	0·99	Pale yellow	II + III		II + III		
2		200	,,	,,	+	53	150		5·6	0·98	,,	II + III		II + III		
3		230	,,	,,	+	36	190		5·8	0·91	Yellow	II + III		II + III	(I)	+
4		180	,,	Steel	—	148	14		4·5	0·89	,,	I	II	Very small		
5		180	48	,,	—	<10	2	<5	6·4	1·00	Pale yellow			II		
6		230	24	,,	—	34	4	<5	5·3	1·00	Pale green			II		
7		180	,,	Glass	—	9790	195		4·1	0·98	Yellow			II		
8		180	,,	,,	—	3717	109		4·4	0·99	Pale yellow			II	III	
9		230	,,	Steel	—	350	64	8	4·9	1·00	,,			II		
10		230	168	,,	—	1300	69	<5	4·3	1·01	Bright yellow			II		
11		230	,,	,,	+	340	30	<5	4·3	0·99	Yellow			II		
12	UO_3 (II) from $UO_3.H_2O$	180	24	Glass	+	109	415	<5	7·1	0·99	Pale yellow			II		
13		230	,,	,,	+	85	32	<5	6·9	0·86	,, ,,			III	(I)	+
14		180	,,	Steel	—	13	3			1·01	,, green			II		
15		280	,,	,,	—	20	1		6·1	1·02	,, ,,	II		II		
16		320	,,	,,	—	14	<1		6·0	0·50	Mustard	$UO_3.0{\cdot}5H_2O$		$UO_3.0{\cdot}5H_2O$		
17	UO_3 (I) from nitrate, but recycled through $UO_3.2H_2O$	180	,,	Glass	—	21	5		7·3		Yellow			I + II		
18		180	70	,,	—	<30	15		6·9	0·93	Yellow-green			II	I, III	
19		230	24	,,	—	240	5	32		0·89	Yellow	II	III	II + III		+
26		230	,,	Pt	—			<5		0·97	Pale green	II	III	II	III	+
21		230	,,	Glass	—	160	6		7·0	0·92	Green			II + III		+
22		230	,,	Pt	—	7	<5	32		0·93		II	I	II (80)	I (20)	
23		230	70	,,	—	<10	<5	30		0·95	Pale green			II + III		
24		230	0·5	,,	—	<10	5	32	6·1	0·92		II	I	II	I	
25		230	5	,,	—			32		0·91	Yellow-green	II	I	II (80)	I (20)	
26		290	30	Steel	—					0·88	Green			II	$UO_3.0{\cdot}5H_2O$	

Notes on Tables 1 *and* 2.

1. The experiments have been arranged in groups with the same starting material and not in chronological order.
2. Experiments in which agitation is indicated were performed by rotating the glass tubes end-over-end at about 1 rev./sec. and by rocking the steel autoclaves above and below horizontal at 0·5 cycle/sec.
3. In uranium trioxide obtained directly from uranyl nitrate ignition, the soluble uranium content could be varied by washing with water at room temperature before heating.
4. The following abbreviations are used to describe the product: I = orthorhombic I hydrate, $UO_3.0{\cdot}8H_2O$; II = orthorhombic II hydrate, $UO_3.1{\cdot}0H_2O$; III = phase III.

When two components are in approximately equal amount, this is indicated by a + sign between them. Parentheses round a minor phase indicate that this was present in trace amount only; figures in parentheses are number percentages obtained by counting under the microscope.

TABLE 2. *Results of heating peroxide-derived* UO_3 *with water.*

	Starting material	Temp.	Time (hr.)	Container	Agitation	Soluble uranium (p.p.m.)	Soluble "N" (p.p.m.)	"N" (p.p.m.) in solid product	pH
27		180	24	Glass	+		6	17	7·4
28		180	,,	,,	—	150			6·3
29		180	,,	Steel	—	30	<1	<5	6·0
30	UO_3 (I) from	180	88	,,	—	14			6·7
31	peroxide	180	24	,,	—	<10		<5	5·2
32		230	,,	Glass	—	<10	38		7·0
33		230	,,	Steel	—	<10	<5		6·7
34		230	240	,,	—	<10	<5	18	7·0
35	UO_3 from	180	12	,,	—	<10	<2		6·2
36	peroxide	180	24	Glass	—		<5		6·8
37	recycled	180	,,	,,	—	25	154		5·9
38	through	230	,,	,,	—	<10	<5		6·7
39	$UO_3.2H_2O$	230	,,	Steel	—	17	1		6·5
40		180	,,	Glass	—				6·7
41		180	,,	Steel	—	17	<1	<5	6·6
42		230	,,	Glass	—		<5		6·7
43	Red UO_3 (I)	230	,,	Steel	—	13	3		6·6
44	from	230	,,	Glass	—		130	6	7·7
45	$UO_3.0{\cdot}8H_2O$	230	,,	Steel	—	468	26		4·7
46		230	,,	,,	—	<10	1	<5	7·0
47		230	,,	,,	—	21	5	<5	5·2
48		230	,,	,,	—	2	<10		5·7

	Product							
	H_2O (mole per U atom)	Colour	X-Ray Major	X-Ray Minor	Optical Major	Optical Minor	Large yellow plates	Remarks
27	0·83	Yellow	I	III	I		+	
28		,,			I + II			
29	0·90	,,	I	II	I	II		
30	0·99	Green	II	I	II	I		
31	0·98	Yellow-green			II	(I)		
32	0·84	Bright yellow			III	II	+	
33	0·98	Pale green	II		II			
34	0·98	Green	II		II		+	
35	0·92	Yellow-green			I	II		
36	0·87	Yellow			I	(II)		
37		Bright yellow			I	II		Added $NaNO_3$
38	0·86	Yellow			III	II (I)	+	
39	0·90	Green-yellow			II (86)	I (14)		
40	0·97	Pale yellow			II	I		
41	0·95	Yellow-green			II (66)	I (34)		
42	0·91	Yellow			II + III		+	
43	0·99	Pale green			II (88)	I (12)		
44					III	II	+	
45		Yellow-green			II			Added $NaNO_3$
46		Pale green			II			,, sodium silicate
47		,,			II			,, silica
48		,,			II			,, boric acid

description of the anhydrous oxide phases is given in the *X*-ray crystallographic section (p. 3540), but for clarity their derivation is shown here :

UO_3 obtained by thermal decomposition of uranyl nitrate, of $UO_3.2H_2O$, and of $UO_3.0{\cdot}8H_2O$, is crystallographically the same and is designated UO_3, phase (I). According to which of the three source materials is used, however, the oxide may differ in such properties as residual soluble uranyl ion.

UO_3 produced from $UO_3.1{\cdot}0H_2O$ (orthorhombic II) by thermal degradation usually shows an oxygen deficiency and has a cubic structure. It is termed UO_3, phase (II), and is brown or red as compared with the yellow-orange of UO_3 (I).

The results are discussed below in terms of the temperature of reaction between the uranium trioxide and water. In cases where relative amounts of the hydrate phases are

given for any one product, these amounts were obtained by visual analysis under the microscope and the figures quoted in col. 14 of Tables 1 and 2 are number percentages.

(i) *Reaction at* 180°. Uranium trioxide obtained by decomposition of nitrate and heated with water in glass or in steel for up to 48 hr. gave orthorhombic II phase as the major product, the soluble uranium content varying over the range 148—9790 p.p.m. (runs 1, 7, 8, 4, and 5).

However, the trioxide prepared by decomposition of peroxide gave the hydrate orthorhombic I phase, or a mixture of this with orthorhombic II, when heated with water for 24 hr. in glass (runs 27 and 28). In steel, for the same time, the major phase obtained was orthorhombic I, but that obtained after 88 hr. was orthorhombic II (runs 29 and 30).

A sample of uranium trioxide from decomposition of peroxide was washed with water at room temperature in an attempt to remove any remaining traces of soluble uranyl ion. This lead to formation of $UO_3,2H_2O$, which was dehydrated at 400°. Heating the oxide obtained (phase I) with water in glass for 24 hr. or in steel for 12 hr. produced orthorhombic I hydrate as the major phase. This uranium trioxide was evidently quite similar to the original material obtained direct from peroxide.

Anhydrous oxide (phase II), obtained by thermal decomposition of orthorhombic II hydrate, when heated with water in glass at 180° for 24 hr., produced only orthorhombic II hydrate in the presence of a soluble uranium content of 109 p.p.m. and 1840 p.p.m. of nitrate in solution (run 12), but with a soluble uranium content of 21 p.p.m. and 22 p.p.m. of nitrate the product consisted of orthorhombic I and II hydrates in about equal amounts (run 17). Reaction of trioxide (II) with steam at 120° also gave pure orthorhombic II hydrate.

It appears that at 180° orthorhombic I hydrate is unstable relative to orthorhombic II hydrate, some evidence having been obtained for its conversion into the latter (*a*) on lowering the pH for heating any particular kind of trioxide with water (runs 29, 31, 28, 27, 36, 35), (*b*) on prolonged heating with water (runs 17, 18), (*c*) by decomposing the orthorhombic I hydrate thermally and attempting its re-formation in water at 180° (runs 40, 41), and (*d*) on heating in water above 200° (see below). Both orthorhombic hydrate phases were stable in air at room temperature.

(ii) *Reaction at* 230°. Uranium trioxide formed by thermal decomposition of either the nitrate or the peroxide produced orthorhombic II hydrate when heated with water at 230° in steel for 1—10 days and in the presence of soluble uranium (<10—350 p.p.m.) (runs 6, 9, 10, 11, 33, 34). In one run (no. 22), thermally decomposed orthorhombic II hydrate, when again heated for 24 hr. with water in platinum, yielded mainly orthorhombic II hydrate with about 20% of orthorhombic I hydrate. Other experiments with the same type of oxide in platinum inserts in the glass tubes gave some evidence that the orthorhombic I hydrate may be formed first but is converted into orthorhombic II hydrate or into phase III on prolonged heating (runs 24, 25, 22, 20, 23). The orthorhombic II hydrate from experiments in which the uranium trioxide was heated with water in glass at this temperature, was usually mixed with varying amounts of phase III which made the product bright yellow (runs 3, 13, 19, 32).

Phase III was not obtained pure and so evidence on its composition is rather scanty; there seem to be some indications that the water content is <0·9 mole per uranium atom (*e.g.*, run 1). In attempts to determine the cause of its formation, samples of trioxide were heated with water in steel, with the addition of 2% of sodium nitrate, sodium silicate, silica, or boric acid, but in each case the product consisted of only orthorhombic II hydrate (runs 45, 46, 47, 48). A similar addition of sodium nitrate did not produce any phase III at 180° (run 37), although in three cases (runs 1, 8, and 27) this phase was observed from experiments in glass tubes at this temperature. Perhaps the high content of soluble uranyl ion caused these conversions. There is some evidence that a relatively high pH may cause the conversion into phase III at 230°; *e.g.*, thermally decomposed orthorhombic I hydrate [UO_3 (I)] heated in glass for 24 hr. gave a higher proportion of phase III at pH 7·7 than at 6·7 (runs 42 and 44). Uranium trioxide (I), obtained by thermal decomposition of $UO_3,2H_2O$ which in turn was obtained by hydrating the anhydrous oxide produced from peroxide, when heated in water for 24 hr. at 230° also gave a product consisting mainly of

orthorhombic II hydrate when the experiment was performed in steel, but phase III in glass (runs 39 and 38).

In some of the experiments, a different form of uranium trioxide hydrate appeared to be formed as a minor constituent. This formed very large, flat, yellow plates and was observed most often in runs which had been performed at 230° and at relatively high pH (see col. 14 of Tables 1 and 2). In all cases except one it was associated with the appearance of phase III hydrate, and the fact that it is another growth habit of this phase was later proved by single-crystal *X*-ray diffraction photographs.

(iii) *Reaction above* 230°. Uranium trioxide (II) was heated with water in steel for 24 hr. at 280° and produced pure orthorhombic II hydrate, but at 320° a new phase appeared (runs 15 and 16). This formed pale yellow, oblique-ended laths and its composition as shown by analysis was $UO_3,0{\cdot}5H_2O$. Uranium trioxide (I), from ignition of nitrate heated with water at 290°, gave mainly orthorhombic II hydrate with 9% of hemihydrate (run 26). Evidently the orthorhombic II hydrate is unstable with respect to the hemihydrate in water above 280°; there is no evidence, however, that either $UO_3,0{\cdot}8H_2O$ or $UO_3,0{\cdot}5H_2O$ occurs as intermediate in the thermal degradation in air of the monohydrate. These results are in general agreement with those of American workers; Katz and Rabinowitz [9] give results which indicate that the hemihydrate is stable in water above 325° and is slowly converted into the monohydrate below 300°.

X-Ray crystallographic data.

$UO_3,2H_2O$. Identical Guinier powder photographs were obtained from dihydrate specimens prepared by the action of water at room temperature on UO_3 (I) obtained by decomposition of either nitrate or peroxide, and by vapour-phase hydration at room temperature of UO_3 (I) of very small particle size.

The visually estimated intensities of the diffraction lines and the measured $\sin^2\theta$ values are given in Table 3. The existence of a number of summation relations involving pairs of $\sin^2\theta$ values makes it probable that the symmetry is monoclinic or higher, and the absence of any appreciable number of summation relations of triplets of independent $\sin^2\theta$ values together with the presence of large numbers of very weak reflections also indicates a monoclinic structure. It has not proved possible to index the reflections unambiguously.

$UO_3,0{\cdot}8H_2O$. Hydrate specimens of composition near to $UO_3,0{\cdot}8H_2O$, referred to as orthorhombic I phase, were obtained from liquid-water reactions described above and by hydration of UO_3 (I) in steam at 120°. Guinier diffraction photographs of the various specimens showed that the diffraction patterns were basically the same. Small differences in the positions of certain lines of the pattern between one specimen and another were attributed to a variation of cell constant with water content. This effect is being investigated further and will be reported later.

The powder photograph was indexed on the basis of an orthorhombic unit cell: $a = 10{\cdot}23 \pm 0{\cdot}01$, $b = 6{\cdot}89 \pm 0{\cdot}01$, $c = 4{\cdot}28 \pm 0{\cdot}01$ Å. The unit cell has a volume of 301·7 Å^3 and contains four formula units of the ideal composition $UO_3,1{\cdot}0H_2O$. The calculated and observed values of $\sin^2\theta$ are given in Table 4 together with the reflection indices. All reflections observed have $(h + k)$, $(k + l)$, and $(h + l)$ equal to $2n$, which indicates a face-centred space-group.

The uranium atoms lie in four-fold special positions, $(000)(\frac{1}{2}\frac{1}{2}0)(\frac{1}{2}0\frac{1}{2})(0\frac{1}{2}\frac{1}{2})$. The cell dimensions for this phase are close to those given by Zachariasen [10] for a "UO_3,H_2O" of prismatic tablet form.

$UO_3,1{\cdot}0H_2O$. Specimens of composition $UO_3,1{\cdot}0H_2O$, orthorhombic II phase, were obtained by the reaction of liquid water with uranium trioxide under a variety of conditions in the temperature range 200—280°. The samples were examined by powder and single-crystal *X*-ray diffraction methods; the crystal system was orthorhombic and the cell dimensions as deduced from measurements of the Guinier photographs were: $a = 5{\cdot}638 \pm 0{\cdot}005$, $b = 6{\cdot}273 \pm 0{\cdot}005$, $c = 9{\cdot}925 \pm 0{\cdot}005$ Å. The volume of the unit cell was

[9] Katz and Rabinowitz, *ibid.*, p. 289.
[10] Zachariasen, reported in "The Chemistry of Uranium," p. 285.

TABLE 3. *Diffraction data on* $UO_3,2H_2O$.

I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$
vvw	0·0065	vvw	0·0233	vvw	0·0535	w	0·0794	vvw	0·1194	w } Diff.	0·1457
vvw	0·0079	vvw	0·0251	s	0·0571	vvw	0·0856	vw	0·1227	w }	0·1475
s	0·0110	vvw	0·0299	ms	0·0591	vw	0·0888	w+	0·1280	m+	0·1545
vvw	0·0141	mw	0·0440	vvw	0·0681	m	0·0903	w+	0·1365	vvw	0·1612
vvw	0·0154	s	0·0462	vvw	0·0690	mw	0·0926	w+	0·1391	vvw	0·1653
vvw	0·0158	ms	0·0485	vw	0·0710	w	0·1115	m−	0·1435	vvw	0·1688
vvw	0·0172	vw	0·0491	vw	0·0737	vvw	0·1153			vw	0·1762

TABLE 4. *Diffraction data on* $UO_3,0{\cdot}8H_2O$.

Index	$\sin^2\theta_{calc.}$	$\sin^2\theta_{obs.}$	$I_{obs.}$	Index	$\sin^2\theta_{calc.}$	$\sin^2\theta_{obs.}$	$I_{obs.}$	Index	$\sin^2\theta_{calc.}$	$\sin^2\theta_{obs.}$	$I_{obs.}$
200	0·0227	0·0227	s	222	0·2024	0·2023	w	313	0·3555	0·3558	w
020	0·0500	0·0500	ms	600	0·2045	0·2044	vw	800	0·3635	0·3639	vvw
111	0·0506	0·0505	s	402	0·2206	0·2204	w	622	0·3842	0·3838	w
220	0·0727	0·0727	m	240	0·2227	0·2225	w	351	0·3960	0·3958	w
400	0·0909	0·0907	mw	620	0·2545	0·2543	w	640	0·4045	0·4046	vw
311	0·0961	0·0959	m	422	0·2706	0·2705	w	133	0·4101 }	0·4101	wd
002	0·1297	0·1298	mw	531	0·2869	0·2871	w	820	0·4135 }		
420	0·1409	0·1408	mw	440	0·2909	0·2908	vw	442	0·4206 }	0·4218	wd
131	0·1506	0·1504	m	113	0·3101	0·3101	w	731	0·4232 }		
202	0·1524	0·1526	mw	711	0·3233	0·3231	w	513	0·4463	0·4462	w
022	0·1797	0·1797	w	042	0·3297	0·3292	vvw	060	0·4500	—	
511	0·1869	0·1868	mw	602	0·3342	0·3338	vw	333	0·4555	0·4561	w
331	0·1960	0·1959	mw	151	0·3506 }	0·3514	wd				
040	0·2000	0·2002	vw	242	0·3524 }						

TABLE 5. *Diffraction data on* $UO_3,1{\cdot}0H_2O$.

hkl	$\sin^2\theta_{calc.}$	$\sin^2\theta_{obs.}$	I	*hkl*	$\sin^2\theta_{calc.}$	$\sin^2\theta_{obs.}$	I	*hkl*	$\sin^2\theta_{calc.}$	$\sin^2\theta_{obs.}$	I
002	0·0241	0·0241	m+	211	0·0959	0·0958	vvw	131	0·1607	0·1603	m
111	0·0398	0·0396	s	004	0·0965	0·0965	w	204	0·1713	0·1714	m−
020	0·0604	0·0603	m+	202	0·0989	0·0989	m	115	0·1846	0·1847	m
021	0·0664	0·0663	vvw	122	0·1032	0·1031	vw−	311	0·1893	0·1893	m
200	0·0748	0·0748	m	104	0·1152	0·1151	vvw	133	0·2089	0·2086	m
022	0·0846	0·0844	m	220	0·1352	0·1350	m	006	0·2272	0·2172	w
133	0·0881	0·0880	m+	024	0·1569	0·1566	m−	224	0·2317	0·2315	m
210	0·0899	0·0900	vvw	222	0·1593	0·1594	m	313	0·2376	0·2375	m

TABLE 6. *Diffraction data on phase III hydrate.*

I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$
s	0·0151	s	0·0288	m	0·0562	m−	0·0961	m−	0·1095	vvw	0·1255
vw	0·0229	vw	0·0414	m	0·0667	vw	0·0973	m−	0·1173	vvw	0·1290
m+	0·0259	m+	0·0531	m−	0·0759	vvw	0·1032	vw	0·1221	m−	0·1357
w	0·0274	m+	0·0536	s	0·0806						

TABLE 7. *Diffraction data for* $UO_3,0{\cdot}5H_2O$.

I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$
vw	0·0111	vvw	0·0346	m	0·0573	vvw	0·0858	w	0·1342	vvw	0·1939
w	0·0125	vw	0·0437	vvw	0·0596	vw	0·0896	vvw	0·1514	vw	0·2001
vw	0·0202	vvw	0·0462	w	0·0617	vw	0·0921	vvwd	0·1552	vvw	0·2069
vw	0·0224	vvw	0·0486	vvw	0·0763	vw	0·0939	vvw	0·1624	vw	0·2136
m−	0·0262	vvw	0·0499	vvw	0·0807	vw	0·0952	w	0·1736	vvw	0·2197
vw	0·0310	w	0·0533	vvw	0·0828	w	0·1296	vvw	0·1746		
m+	0·0335	m	0·0551	vvw	0·0847						

TABLE 8. *Diffraction data on* UO_3, *phase (I).*

I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$	I	$\sin^2\theta_{obs.}$
mw	0·0139	sd	0·0638	wd {	0·1231	mw	0·1495	w	0·1929	mwd	0·2494
ms	0·0237	vw	0·0688		0·1238	w } d	0·1629	mw	0·1952	wd {	0·2547
vw	0·0257	sd	0·0758	vw	0·1252	w }	0·1642	m	0·1997		0·2563
s	0·0309	w	0·0785	w	0·1295	mwd {	0·1743	vvw	0·2025	vw	0·2736
vs	0·0497	mw	0·0854	w	0·1333		0·1760	vw	0·2145	vw	0·2855
ms	0·0559	vw	0·0995	vvw	0·1350	mw	0·1785	mw	0·2234		
vw	0·0567	w	0·1033	mw	0·1454	w	0·1852	mw	0·2329		

351 Å^3, and on the assumption of an oxygen volume of about 19 Å^3 the cell contained four formula units UO_3,H_2O.

The calculated and observed values of $\sin^2\theta$ together with the Miller indices and visually estimated intensities of the powder reflection lines are set out in Table 5. The indices of all the reflections except a few weak ones satisfy the conditions $(h + k) = (k + l) = (h + l) = 2n$. A close examination of the powder photographs and the single-crystal Weissenberg photographs discloses weak reflections with the indices (021), (104), (210), (211), (122). The conditions limiting all observed reflections are $(0kl)$, $k = 2n$; $(h0l)$, $l = 2n$; $(hk0)$, $h = 2n$; (hkl), no conditions. The space-group is consequently $Pbca$–O_{2h}^{15}.

The general position of $Pbca$ is 8-fold and the co-ordinates of two sets of 4-fold positions are: $(000)(\frac{1}{2}\frac{1}{2}0)(\frac{1}{2}0\frac{1}{2})(0\frac{1}{2}\frac{1}{2})$, $(00\frac{1}{2})(\frac{1}{2}\frac{1}{2}\frac{1}{2})(\frac{1}{2}00)(0\frac{1}{2}0)$. These differ only in the choice of origin and the point symmetry is $\bar{1}$. Hence the uranium atoms must lie in a set of four-fold positions on a face-centred lattice. In these positions they make maximum possible contribution to the reflections with $(h + k)$, $(k + l)$, and $(h + l)$ even, and zero contribution to all other classes of reflections. This accounts for the distribution of intensities observed, the very weak reflections being derived from oxygen-scattering only.

$UO_3,?H_2O$, Phase III. This substance appeared in the product of experiments in which uranium trioxide was heated with water at 230° in glass tubes. Both the chemical and *X*-ray analyses were hampered by the fact that it was never prepared with purity exceeding 50%. The powder diffraction photograph was extremely complex; the $\sin^2\theta$ values of the most prominent lines are presented in Table 6. The absence of any summation relations between these $\sin^2\theta$ values indicates that the crystals are probably triclinic.

$UO_3,0{\cdot}5H_2O$. The hemihydrate was produced as a pure phase by reaction of uranium trioxide with water at 320°. The crystals were yellow, oblique-ended laths about ten microns long. They were often irregularly fractured and striated in appearance, and they showed imperfect extinction between crossed polaroids. Because of extensive twinning of the crystals it has not proved possible to determine unit-cell dimensions; however, for identification purposes Table 7 gives the intensities and $\sin^2\theta$ of the most prominent powder diffraction lines.

UO_3 (I). Anhydrous uranium trioxide samples, obtained by thermal decomposition of uranyl nitrate, $UO_3,2H_2O$, or $UO_3,0{\cdot}8H_2O$ are crystallographically indistinguishable. They are also indistinguishable from the product of oxidation of lower uranium oxides with 130 atm. of oxygen at 700°. The *X*-ray pattern is complex and contains many weak lines; some summation relations which exist between pairs of $\sin^2\theta$ values indicate that the compound may be monoclinic. For identification purposes, the observed $\sin^2\theta$ values and visually estimated intensities are shown in Table 8.

UO_3 (II). Dehydration of orthorhombic II monohydrate in air at 415° produces a red trioxide with simple cubic structure and a unit cell dimension of $a = 4{\cdot}146 \pm 0{\cdot}005$ Å. If the monohydrate is heated very rapidly to this temperature specimens slightly deficient in oxygen (down to $UO_{2{\cdot}86}$) are produced.[11] The cell contains one formula unit UO_3, there being uranium at (000) and oxygen at $(\frac{1}{2}00)$, $(0\frac{1}{2}0)$, and $(00\frac{1}{2})$. The compound is isostructural with rhenium trioxide.

The authors thank T. Johnston, R. S. Street, and Miss G. W. Booth for assistance in the experimental work, and Dr. R. W. M. D'Eye for discussion of the *X*-ray data. Analyses for particle size, nitrate content, and soluble uranium were performed by Chemical Inspectorate, Chatham, by arrangement with Mr. J. Walkden. Some samples of anhydrous uranium trioxide were analysed for oxygen content by Mr. E. A. Harper, a volumetric method being used.

U.K. Atomic Energy Authority,
Harwell, Didcot, Berks.

[*Received, November 10th*, 1955.]

[11] Wait, *J. Inorg. Nuclear Chem.*, 1955, **1**, 309.

684. *Ethyl* p-*Nitrobenzoylethoxaloacetate.*

By J. Forrest, S. B. Hansen, and V. Petrow.

Ethyl *p*-nitrobenzoylethoxaloacetate (V) has been prepared from *p*-nitrobenzoyl chloride and ethyl ethoxaloacetate. Its hydrolytic transformations have been studied and its conversion into *p*-nitrophenacyl bromide (III) and *p*-nitroacetophenone achieved.

Conversion of *p*-nitrobenzoic acid (I) into *p*-nitroacetophenone (IX) may be effected through intermediates of the β-keto-ester type. Thus *p*-nitroacetophenone is obtained (i) by hydrolytic decarboxylation of ethyl *p*-nitrobenzoylmalonate (VIII; $R' = R'' = CO_2Et$), prepared from *p*-nitrobenzoyl chloride and ethyl sodio-[1] or ethoxymagnesio-malonate,[2] or (ii) by reaction[3] of ethyl *p*-nitrobenzoylacetoacetate[3] (VIII; $R' = Ac$, $R'' = CO_2Et$) with 30% sulphuric acid.[4] A third route, which forms the subject of the present communication, lies in the use of ethyl ethoxaloacetate, an intermediate rarely employed hitherto for ketone synthesis.[5] It offers advantages over ethyl malonate and ethyl acetoacetate, however, in that the intermediate *p*-nitrobenzoylethoxaloacetate (V) may be converted directly, not only into the acetophenone (IX), but also into the valuable intermediate (III) as indicated below.

Preliminary experiments showed that condensation of *p*-nitrobenzoyl chloride with ethyl sodioethoxaloacetate, followed by hydrolysis of the total product with sulphuric acid–acetic acid, led to *p*-nitrobenzoic acid (I), *p*-nitroacetophenone (IX), and compound A, $C_{22}H_{18}O_{11}N_2$, of which only the second was required. Examination of the products of condensation before hydrolysis revealed the complex nature of the initial condensation. Thus compound A was also obtained from those condensations of *p*-nitrobenzoyl chloride and ethyl sodioethoxaloacetate that yielded the intermediate ethyl *p*-nitrobenzoylethoxaloacetate (V) in poor yield. Occasional experiments giving the intermediate (V) in relatively good yield, in contrast, furnished small quantities of an isomeric compound B. We were obliged, consequently, to study the initial condensation in greater detail. The work was simplified by the observation that the intermediate (V) (essentially pure) was completely extracted from the reaction products by sodium hydrogen carbonate solution. In this way the yield of this intermediate was found to be governed largely by the purity of the *p*-nitrobenzoyl chloride, prepared in this instance by heating *p*-nitrobenzoic acid with thionyl chloride and a little pyridine. Even slight contamination of the acid chloride with pyridine (hydrochloride) drastically lowered the yield of the intermediate (V) with concomitant increase in the quantity of compound A. Traces of undesirable impurities were, however, readily removed by shaking the *p*-nitrobenzoyl chloride solution, before use, with alumina or activated charcoal. A similar, but less marked, deleterious effect was produced by traces of hydroxylic solvents in the reaction medium. Rapid mixing of the components proved desirable. By paying careful attention to detail, the yield of the intermediate (V) was ultimately raised to 70%.

Hydrolysis of this diester (V) with sulphuric–acetic acid gave a 1 : 2 mixture of *p*-nitrobenzoic acid and *p*-nitroacetophenone. As only the latter was required, this stage was further studied.

Hydrolysis with very dilute hydrochloric acid gave ethyl *p*-nitrobenzoylacetate (VI) and *p*-nitrobenzoylpyruvate (II), whose constitutions were confirmed by direct comparison with an authentic specimen[3] in the case of the former and by alternative synthesis[6] of the latter from *p*-nitroacetophenone and ethyl oxalate. The nitrobenzoylacetate could not be reconverted into the diester (V), nor could the latter be prepared from the sodium salt of the pyruvate (I) and ethyl chloroformate. Vigorous hydrolysis of the

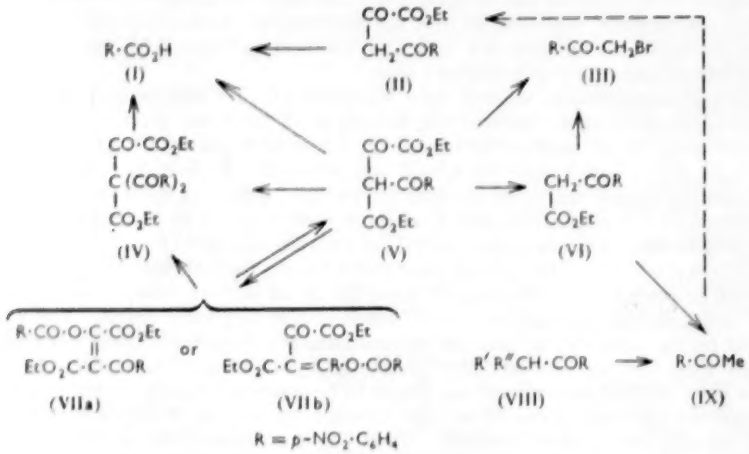
[1] Jackson and Whitmore, *J. Amer. Chem. Soc.*, 1915, **37**, 1929.
[2] Long and Troutman, *ibid.*, 1949, **71**, 2474.
[3] Bülow and Hailer, *Ber.*, 1902, **35**, 931.
[4] Gevekodt, *Annalen*, 1883, **221**, 335.
[5] See, however, Nef, *ibid.*, 1893, **276**, 22.
[6] Cf. *Org. Synth.*, **6**, p. 40, for method used.

p-nitrobenzoyl acetate (VI) with sulphuric–acetic acid furnished *p*-nitroacetophenone (IX) in almost quantitative yield: the pyruvate (II), in contrast, gave solely *p*-nitrobenzoic acid (I) under these experimental conditions.

Ethanolysis of the diester (V), or alternatively its hydrolysis with glacial acetic acid at 95°, gave a high yield of the *p*-nitrobenzoylacetate (VI). Conversion of the diester (V) to *p*-nitroacetophenone (IX) with minimal formation of by-products is thereby achieved.

The marked reactivity of the diester (V) has been additionally utilised in developing a new route to *p*-nitrophenacyl bromide (III). Bromination in acetic acid, followed by dilution with water and heating, gave the phenacyl bromide (III) directly and in high yield. The benzoylacetate (VI) was likewise converted into the bromide (III) with negligible formation of *p*-nitrobenzoic acid. The pyruvate (II), in contrast, gave only *p*-nitrobenzoic acid on similar treatment.

The empirical formulæ of compounds A and B corresponded to that of an ethyl di-*p*-nitrobenzoylethoxaloacetate. Compound B differed from A in its readier hydrolysis (see below) and characteristically in its being irreversibly transformed into its isomer by



such reagents as hot aqueous acetic acid, potassium carbonate suspended in ethyl acetate, catalytic quantities of a tertiary base in a non-polar solvent, and partly even in hot ethanol. It was also more readily soluble than compound A in hydroxylic solvents. These differences recall the contrasting properties of ethyl *O*- and *C*-acetylacetoacetate, the former being transformed into the latter by alkaline reagents such as potassium carbonate suspended in ethyl acetate.[7] The structures ethyl αα-di-*p*-nitrobenzoyl-α-ethoxaloacetate (IV) and the *O*-acyl-ester (VIIa or b) * are consequently assigned to compounds A and B respectively, though attempts to confirm them by synthesis were not wholly successful. Presumptive evidence in favour of the assigned formulations, however, is furnished by the observations that (i) compound B is formed in high yield by condensing the sodium salt of the diester (V) with *p*-nitrobenzoyl chloride in a non-polar solvent, (ii) the presence of an unsaturated linkage (infrared spectrum) in compound B, and (iii) the preparation of the ester (IV) in low yield (15%) by direct condensation of the intermediate (V) with *p*-nitrobenzoyl chloride in a non-polar solvent and in high yield when equimolar proportions of these components were mixed in an inert solvent in the presence of a molar equivalent of a tertiary base. The reactions, however, lack diagnostic significance.[8]

* The latter was kindly suggested by a referee.

[7] Claisen and Zedel, *Annalen*, 1893, **277**, 175; Claisen and Hoas, *Ber.*, 1900, **33**, 3780.

[8] See, for example, James, *Annalen*, 1884, **226**, 211; Michael, *Ber.*, 1905, **38**, 2088; Mirgasson, *Bull. Soc. chim. France*, 1886, **45**, 716.

Prolonged ethanolysis of compound B with 95% ethanol gave *p*-nitrobenzoic acid (I) as the major product, together with small quantities of compound A (IV). Careful hydrolysis with a molar equivalent of ethanolic potassium hydroxide gave three products, (I), (IV), and (V). Compound A (IV), in contrast, was largely unaffected by prolonged heating with ethanol: it slowly gave *p*-nitroacetophenone and *p*-nitrobenzoic acid (I) in the proportion of 1 : 2 on vigorous hydrolysis with sulphuric–acetic acid. Concentrated sulphuric acid converted it into ethyl *p*-nitrobenzoylacetate (VI) with larger quantities of *p*-nitrobenzoic acid.

Experimental

Ethyl p-*Nitrobenzoylethoxaloacetate* (V).—(*a*) *p*-Nitrobenzoyl chloride (18·5 g.) (preferably distilled; alternatively the solution of the crude acid chloride may be shaken for a few minutes with alumina before use) in dichloroethylene (50 ml.) was added rapidly at room temperature to technical ethyl sodioethoxaloacetate (21 g., 1 mol.) in dichloroethylene (100 ml.). After 20 minutes' shaking at <30° (cooling), the mixture was extracted twice with 3% sodium hydrogen carbonate solution (150 and 100 ml.). Acidification (Congo-red) of the combined extracts with 5% hydrochloric acid gave *ethyl* p-*nitrobenzoylethoxaloacetate* (V) (50%), large pale yellow rhombs, m. p. 80—82° (Found: C, 53·4; H, 4·6; N, 4·6. $C_{15}H_{15}O_8N$ requires C, 53·4; H, 4·4; N, 4·2%), after crystallisation from benzene–light petroleum (b. p. 40—60°).

(*b*) By using 2 mols. of ethyl sodioethoxaloacetate, the yield of product (V) was raised to 65—70%.

Ethyl α-p-*Nitrobenzoyl*-α′-p-*nitrobenzoyloxyfumarate* (VIIa) *or* α-*Ethoxalo*-β-p-*nitrophenyl*-β-p-*nitrobenzoyloxyacrylate* (VIIb).—(*a*) The dichloroethylene liquors from experiment (*a*) (above) were washed with water and evaporated to dryness under reduced pressure and the residue slowly crystallised from benzene–light petroleum (b. p. 40—60°), to give the *ester* (VIIa or b) (5—6 g.), feathery needles, m. p. 108—110° (Found: C, 54·2; H, 3·7; N, 5·6. $C_{22}H_{18}O_{11}N_2$ requires C, 54·3; H, 3·7; N, 5·7%).

(*b*) The ester (V) (17 g.) in dichloroethylene (100 ml.) was treated with stirring with sodium ethoxide (1·2 g. of sodium in 35 ml. of ethanol). After 10—15 min. the mixture was carefully taken to dryness under reduced pressure and dichloroethylene (100 ml.) was added, followed by *p*-nitrobenzoyl chloride (9·25 g. in 75 ml. of dichloroethylene). Stirring was continued for a further 30 min. Precipitated sodium chloride was removed, and the filtrate washed with cold 3% sodium hydrogen carbonate solution (200 ml.) and then water, dried, and evaporated under reduced pressure. The residue in ethanol (*ca.* 80 ml.) was filtered to remove *p*-nitrobenzoic anhydride (*ca.* 1 g.; m. p. 190°) and set aside, giving compound B, m. p. 109—110° (Found: C, 54·4; H, 3·5; N, 5·3%), not depressed in admixture with a sample obtained as in (*a*).

Ethyl αα-*Di*-p-*nitrobenzoyl*-α-*ethoxaloacetate* (IV).—(*a*) Crude *p*-nitrobenzoyl chloride (18·5 g.) in dichloroethylene (50 ml.) was added rapidly at room temperature to ethyl sodioethoxaloacetate (21 g.) in dichloroethylene (100 ml.). After 15 minutes' shaking the solvents were removed under reduced pressure and the residue hydrolysed for *ca.* 3 hr. with hot acetic acid (30 ml.), water (10 ml.), and concentrated sulphuric acid (6 ml.). The mixture was poured into water (200 ml.), extracted with chloroform and filtered to remove *p*-nitrobenzoic acid (I), the chloroform removed, and the residue crystallised from ethanol (charcoal), to give *ethyl* αα-*di*-p-*nitrobenzoyl*-α-*ethoxaloacetate*, pale yellow needles, m. p. 145—146° (Found: C, 54·4; H, 3·4; N, 5·3. $C_{22}H_{18}O_{11}N_2$ requires C, 54·3; H, 3·7; N, 5·7%).

(*b*) Compound B (12 g.) in dichloroethylene containing 3 drops of piperidine was heated under reflux for 1 hr. The product, from ethanol–ethyl acetate, furnished the *CC*-diacyl derivative (IV), m. p. 144—145° (Found: C, 54·7; H, 3·4; N, 5·5%) not depressed in admixture with a sample prepared as in (*a*).

(*c*) The diester (V) (10 g.) in dichloroethylene (50 ml.) was treated with *p*-nitrobenzoyl chloride (5·4 g.). After 2 hr., the mixture was washed with 3% sodium hydrogen carbonate solution and then water, dried, and evaporated and the residue crystallised from ethanol, giving the diacyl derivative (IV), m. p. 144—145° alone or in admixture with an authentic specimen.

(*d*) The diester (V) (34 g.) in dichloroethylene (100 ml.) was mixed with *p*-nitrobenzyl chloride (18·5 g.), followed immediately by pyridine (7·8 g.). The temperature of the mixture rose to 40° and a little pyridine hydrochloride separated. Working up as in (*c*) furnished the product (IV), m. p. and mixed m. p. 144—146°.

Acid Hydrolysis of Ethyl αα-*Di*-p-*nitrobenzoyl*-α-*ethoxaloacetate* (IV).—This ester (20 g.) and

concentrated sulphuric acid (25 ml.) were left at room temperature for 1 hr.; carbon dioxide was evolved. The mixture was poured into water (500 ml.) and mixed with chloroform (150 ml.); *p*-nitrobenzoic acid (9 g.) separated and was removed (a further 2 g. were extracted from the chloroform solution with aqueous sodium hydrogen carbonate). The chloroform was then removed and the residue taken up in benzene (10 ml.) and light petroleum (15 ml.) (b. p. 40—60°); the solution was filtered and evaporated and the residue crystallised from ethanol, giving ethyl *p*-nitrobenzoylacetate, yellow needles, m. p. 79—80° (Found: C, 56·0; H, 4·3; N, 5·5. Calc. for $C_{11}H_{11}O_5N$: C, 55·7; H, 4·6; N, 5·9%).

*Hydrolysis of Ethyl α-*p*-Nitrobenzoylethoxaloacetate* (V).—(*a*) This ester (50 g.) was heated with sulphuric–acetic acid–water (5 : 3 : 1 v/v; 100 ml.) at 95—100° with stirring for 1½ hr. Ethyl acetate slowly distilled off. The mixture was poured into water (500 ml.) and extracted with chloroform (2 × 100 ml.), and *p*-nitrobenzoic acid (7 g.) was filtered off. The chloroform extracts yielded *p*-nitroacetophenone (IX) (14 g.), m. p. and mixed m. p. 80°.

(*b*) The ester (V) (10 g.) in water (140 ml.) and hydrochloric acid (10 ml.) was stirred at 80—83° for ½ hr., then extracted with chloroform and the extract shaken with concentrated aqueous sodium hydrogen carbonate solution (2 × 50 ml.) to remove unchanged material (1·2 g.). Removal of chloroform, followed by crystallisation from ethanol, furnished ethyl *p*-nitrobenzoylacetate (VI) (4·4 g.), yellow needles, m. p. and mixed m. p. 79—80° (Found: C, 55·6; H, 4·4; N, 6·1. Calc. for $C_{11}H_{11}O_5N$: C, 55·7; H, 4·6; N, 5·9%).

(*c*) The mixture as in (*b*) was heated under reflux for 30 min. and the product isolated with chloroform. The non-aqueous fraction was shaken with sodium hydrogen carbonate solution and filtered from yellow solids. The latter were acidified, to give *ethyl* p-*nitrobenzoylpyruvate* (II) (1·75 g.), m. p. 116—117° after crystallisation from ethanol (Found: C, 54·4; H, 4·3; N, 5·2. $C_{12}H_{11}O_6N$ requires C, 54·4; H, 4·2; N, 5·3%). The chloroform liquors yielded ethyl *p*-nitrobenzoylacetate (VI) (2·5 g.).

(*d*) Ethyl *p*-nitrobenzoylacetate (VI), pale yellow needles, m. p. and mixed m. p. 78—79°, was obtained by heating the ester (V) (25 g.) in ethanol (60 ml.) for 1 hr. and then allowing the solution to cool.

Hydrolysis of the *p*-nitrobenzoylacetate with sulphuric–acetic acid–water as above gave *p*-nitroacetophenone in 90% yield.

(*e*) Heating the diester (V) (50 g.) with ethanol (100 ml.) for 1 hr., followed by removal of solvent under reduced pressure and acid hydrolysis as above, gave *p*-nitroacetophenone in 90% yield.

(*f*) The diester (V) (10 g.) was heated with glacial acetic acid (40 ml.) for 2 hr. at 95°. Pouring the mixture into water then gave ethyl *p*-nitrobenzoylacetate (93%), m. p. 79—80° after crystallisation from ethanol.

(*g*) The diester (V) (10 g.) was heated with glacial acetic acid (40 ml.) for 2 hr. at 95°, then sulphuric acid (15 g.) in water (20 ml.) was added and heating continued for a further 3 hr. Precipitation with water (200 ml.) and isolation with chloroform gave *p*-nitroacetophenone (85%), m. p. 80° (from ethanol).

Ethyl p-*Nitrobenzoylpyruvate* (II).—Ethyl oxalate (75 g.), mixed with *p*-nitroacetophenone (82·5 g.), was added at 20° to a stirred solution of sodium ethoxide (from 12·5 g. of sodium in 280 ml. of ethanol) during 1½ hr. Stirring was continued for a further 1 hr., then the mixture was poured into water (500 ml.) and immediately acidified to Congo-red, and the product was isolated with chloroform, to give the pyruvate (II) (70 g.), pale yellow needles, m. p. 115—116° (Found: C, 54·6; H, 3·8; N, 5·0%), not depressed in admixture with a sample prepared from the ester (V) as above.

Hydrolysis of the pyruvate with sulphuric-acetic acid–water gave *p*-nitrobenzoic acid in 90% yield.

p-*Nitrophenacyl Bromide* (III).—The diester (V) (20 g.) in acetic acid (45 ml.) was treated with bromine (9·3 g.) in one portion. After stirring to ensure homogeneity, the mixture was heated to 95—100° and there maintained for 10 min. Water (7·5 ml.) was added and heating continued for a further 1—1½ hr. Water (20 ml.) was then added and the mixture allowed to cool. *p*-Nitrophenacyl bromide (11 g.) separated and formed straw-coloured needles, m. p. and mixed m. p. 98—99° (Found: C, 39·6; H, 2·5; N, 5·4. Calc. for $C_8H_6O_3NBr$: C, 39·3; H, 2·5; N, 5·7%), from light petroleum (b. p. 40—60°).

Ethyl *p*-nitrobenzoylacetate (VI) (23·7 g.) similarly gave the bromide (80%), m. p. and mixed m. p. 98—99° (Found: C, 39·5; H, 2·7; N, 5·3%).

Ethyl *p*-nitrobenzoylpyruvate gave *p*-nitrobenzoic acid on similar treatment.

Ethanolysis of Compound B.—The compound (10 g.) in 95% ethanol (50 ml.) was heated

under reflux for 4 hr., then allowed to cool, and the *CC*-diacyl compound (IV) (3 g.) removed by filtration. Removal of solvent under reduced pressure and treatment of the residue with chloroform gave *p*-nitrobenzoic acid (1·5 g.), which was filtered off. Removal of solvent and crystallisation from ethanol (5 ml.) at 0° gave ethyl *p*-nitrobenzoylacetate (VI) (1·0—1·5 g.), m. p. 79°—80°.

Alkaline Hydrolysis of Compound B.—The compound (2 g.) was added to potassium hydroxide (250 mg.) in 95% ethanol (15 ml.), and the solution immediately refluxed for 2—3 min., poured into water (80 ml.), acidified to Congo-red, and extracted with chloroform (2 × 10 ml.). The combined extracts were washed with water and extracted with 3% sodium hydrogen carbonate solution (2 × 25 ml.), which was then acidified to Congo-red. The precipitated solids (800 mg.) were collected and separated by chloroform treatment into *p*-nitrobenzoic acid (350 mg.) and a soluble fraction which gave ethyl α-*p*-nitrobenzoylethoxaloacetate (V), m. p. and mixed m. p. 80—82°. The original chloroform extracts, after evaporation and trituration of the residue with ethanol (10 ml.), gave the *CC*-diacyl compound (IV) (250 mg.), m. p. and mixed m. p. 144—145°.

The authors thank the Directors of The British Drug Houses Ltd. for permission to publish this work and Mr. R. F. Branch, B.Sc. (Ministry of Supply) for the infrared data.

Chemical Research Laboratories, The British Drug Houses Ltd.,
London, N.1. [*Received, November 23rd*, 1955.]

---

685. *The Chemistry of Fungi. Part XXVI.* Dechloronornidulin.*

By F. M. Dean, A. D. T. Erni, and Alexander Robertson.

The isolation of dechloronornidulin $C_{19}H_{16}O_5Cl_2$ from a strain of *Aspergillus nidulans* is reported. The new compound belongs to the same series as nidulin and may be identical with the substance previously called "ustin II." A partial structural formula is advanced.

Further examination of the mycelium of the non-ascosporic strain of *Aspergillus nidulans* which produced nidulin [1] (I; R′ = Me, R″ = H) and nornidulin ("ustin") (I; R′ = R″ = H) has disclosed the presence of a third metabolite of the same general type. The new member of the series has m. p. 212—214°, a molecular formula $C_{19}H_{16}O_5Cl_2$, and an ultraviolet spectrum closely similar to that of nidulin, and may, therefore, be identical with Compound II ("ustin II") isolated by Hogeboom and Craig [2] for which these authors give m. p. 214—216° and suggest a molecular formula $C_{21}H_{18}O_6Cl_2$. The name dechloronornidulin is now proposed for the new substance.

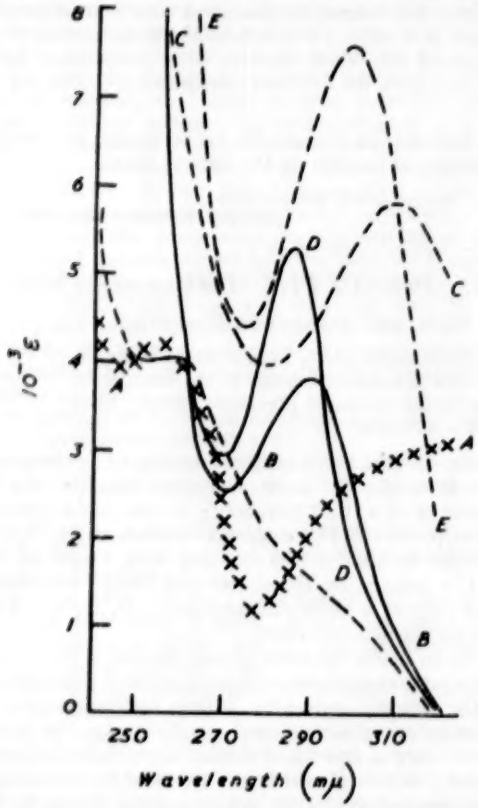
Like nornidulin, dechloronornidulin is an acidic dihydric phenol devoid of methoxyl groups, forming a dimethyl ether with the same characteristic lactonic-carbonyl absorption at 1733 cm.$^{-1}$ (Nujol). Disruption of the lactonic system by sodium methoxide gave a phenolic ester, methyl dechloro-*OO*-dimethylnornidulinate, and, on fission by the nitric acid method used originally to isolate the ring A moiety of methyl *O*-methylnidulinate, this compound gave two monochlorinated products of which one appeared to be a nitro-derivative of the other. By synthesis, these degradation products were shown to be methyl 6-chloro- (II; R = H) and 6-chloro-4-nitro-everninate † (II; R = NO_2). Because in the nitric acid fission methyl *O*-methylnidulinate gave methyl dichloroeverninate, the present result could not be attributed to the extrusion of a chlorine atom from a dichlorinated ring A in dechloronornidulin and hence it was inferred that ring A contains but one chlorine atom.

Accordingly the partial formulæ (III; R = H) and (IV) may be allocated to dechloronornidulin and to methyl dechloro-*OO*-dimethylnornidulinate respectively. The residue B of dechloronornidulin (III; R = H) appears to be identical with the ring B of nornidulin (I; R′ = R″ = H); thus neither compound couples with diazonium salts or

* Part XXV, *J.*, 1955, 1432.
† Me is numbered 1 in these trivial names.

[1] Dean, Roberts, and Robertson, *J.*, 1954, 1432.
[2] Hogeboom and Craig, *J. Biol. Chem.*, 1946, **162**, 363.

Gibb's reagent, and methyl dechloro-*OO*-dimethylnornidulinate (IV), like methyl *O*-methylnidulinate, behaves as a phenol towards alkalis and in alcohol has a pronounced peak in the ultraviolet spectrum at about 282 (ε 9810) (see Figure) similar to those of several polyhydric phenols and in a region in which both methyl 6-chloro- and 4 : 6-dichloroeverninate have minima. This allocation is confirmed by the bathochromic shifts shown by methyl *O*-methylnidulinate and by methyl *OO*-dimethyl*neo*nidulinate when alkali is added to their alcoholic solutions, a behaviour which is characteristic of phenols and cannot be due to ring A, even though this ring undoubtedly exerts some effect on the ring-B absorption by reason of the poor insulating properties of the diphenyl oxygen atom.



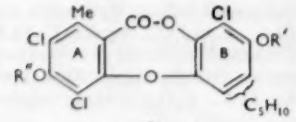
Absorption spectra (10^{-4}M-*solutions in* EtOH) *of :*

A, methyl 4 : 6-*dichloroeverninate; B, methyl* O-*methylnidulinate; C, solution B with added alkali; D, methyl dechloro*-OO-*dimethylnornidulinate; and E, solution D with added alkali.*

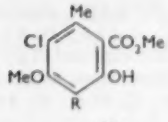
Typical spectra are given in the Figure. Further evidence relating the rings B of nidulin and dechloronornidulin will form part of a later communication dealing with the C_5 residue.

By Gattermann's method 4-chloro-orcinol was converted into 3-chloro-4 : 6-dihydroxy-2-methylbenzaldehyde (V; R = CHO), the di(methoxycarbonyl) derivative of which on oxidation with potassium permanganate and subsequent hydrolysis furnished 6-chloro-orsellinic acid (V; R = CO_2H). To exclude the possibility that the aldehyde group had been introduced into the 4-position of the orcinol ring (Me = 1), the isomeric 3-chloro-*p*-orsellinic acid (VI) was prepared by monochlorination of methyl *p*-orsellinate followed by hydrolysis of the resulting ester and was clearly different from the acid (V; R = CO_2H). Selective methylation of 6-chloro-orsellinic acid by diazomethane afforded methyl 6-chloro-everninate (II; R = H) having the properties of an *o*-hydroxy-ester and being identical with the non-nitrogenous degradation product. Although nitration of this ester supplied methyl 6-chloro-4-nitroeverninate (II; R = NO_2) identical with the second degradation

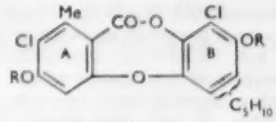
product, the reaction appeared to be more sluggish than that occurring during the degradation. This result can hardly be due to a comparatively rapid substitution of the intact diphenyl ether, followed by fission, because dechloro-*OO*-dimethylnornidulin cannot be



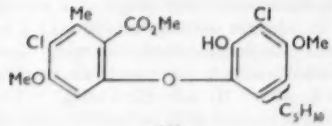
(I)



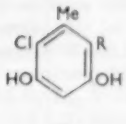
(II)



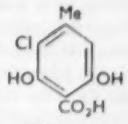
(III)



(IV)



(V)



(VI)

nitrated even at 80°. Therefore it is reasonable to attribute the increased rate to the well-established catalysis of nitration of phenols and their derivatives by nitrous acid, here produced by oxidation of the ring B fragment.

Experimental

Dechloronornidulin (III; R = H).—*Aspergillus nidulans* (NRRL, No. 2006) was cultivated by the method described in Part XXII [1] and the dried and powdered mycelial felt from 50 l. of culture medium was exhaustively extracted with light petroleum (b. p. 40—60°). The semisolid extract left on evaporation of the solvent was dissolved in ether (500 ml.), and shaken with 10% aqueous sodium carbonate, forming three layers. On acidification the small dark middle layer yielded crude nidulin, whilst the lowest layer gave, on some occasions, a mixture of nidulin and nornidulin, and on others, a mixture of nidulin and dechloronornidulin. Some increase in the proportion of dechloronornidulin seemed to result from the use of culture media with a somewhat reduced chloride content, but unfortunately the production of this compound was too erratic to allow a satisfactory assessment. *Dechloronornidulin* was freed from nidulin by repetition of the sodium carbonate extraction and on crystallisation from methanol formed needles (0·8 g.), m. p. 212—214°, $\lambda_{max.}$ (in EtOH) 264 mμ (ε 9810), having a negative ferric reaction [Found: C, 57·7; H, 4·2; Cl, 18·2%; OMe, negative; *M* (micro-Rast), 356 (decomp.). $C_{19}H_{18}O_5Cl_2$ requires C, 57·7; H, 4·1; Cl, 17·9%; *M*, 395]. This compound was readily soluble in aqueous sodium hydrogen carbonate containing a few drops of alcohol.

Dechloro-OO-*dimethylnornidulin* (III; R = Me).—In refluxing acetone (20 ml.), containing potassium carbonate (0·5 g.), dechloronornidulin (0·2 g.) reacted with methyl iodide (5 ml.) during 3 hr. to give the *dimethyl ether* which on isolation formed rhombs (0·18 g.), m. p. 156—156° from methanol, $\lambda_{max.}$ 223, 260 mμ (ε 17,600, 4130), insoluble in cold aqueous 2N-sodium hydroxide [Found: C, 59·3; H, 4·7; OMe, 15·0%; *M* (Micro-Rast), 406. $C_{19}H_{14}O_5Cl_2(OMe)_2$ requires C, 59·6; H, 4·7; OMe, 14·7%; *M*, 423].

Methyl Dechloro-OO-*dimethylnornidulinate* (IV).—A solution of the aforementioned ether (0·2 g.) in methanol (40 ml.), containing sodium methoxide (from 0·011 g. of sodium), was gently boiled for 6 hr. and the solvent removed with a current of air. A solution of the residue in ether was washed with dilute sulphuric acid followed by water, dried, and evaporated, leaving a yellow gum which solidified in contact with light petroleum (b. p. 60—80°). Crystallised from aqueous methanol, this gave *methyl dechloro*-OO-*dimethylnornidulinate* in squat prisms (0·12 g.), m. p. 125—126°, with a negative ferric reaction in alcohol [Found: C, 57·6; H, 5·3; OMe, 20·4. $C_{19}H_{15}O_5Cl_2(OMe)_3$ requires C, 58·0; H, 5·3; OMe, 20·4%]. This ester, which was insoluble in aqueous sodium hydrogen carbonate solution, dissolved in 2N-aqueous sodium hydroxide but did not yield dyes with diazotised sulphanilic acid or with Gibb's reagent. In neutral alcohol it had $\lambda_{max.}$ 284 mμ (ε 5460) which changed on addition of one drop of 1% alcoholic potassium hydroxide to $\lambda_{max.}$ 300 mμ (ε 7600). Under the same conditions methyl *O*-methylnidulinate had $\lambda_{max.}$ 290 mμ (ε 3800) in neutral alcohol, changing to $\lambda_{max.}$ 310 mμ (ε 5750) on addition of a drop of 1% alcoholic potassium hydroxide.

6-Chloro-o-orcylaldehyde (V; R = CHO).—A mixture of anhydrous zinc cyanide (1 g.), 4-chloro-orcinol (4 g.), and dry ether (40 ml.) at 0° was saturated with hydrogen chloride during 2 hr. and next day the precipitated aldimine complex was washed with ether and hydrolysed with water (60 ml.) on the steam-bath. The resulting *6-chloro-o-orcylaldehyde* separated from dilute alcohol in prisms (3·9 g.), m. p. 171—173°, soluble in 2N-aqueous sodium hydroxide and having a purple ferric reaction (Found: C, 51·5; H, 4·0; Cl, 19·5. $C_8H_7O_3Cl$ requires C, 51·5; H, 3·8; Cl, 19·0%). Acetylation of this compound (1 g.) by the standard methods gave *6-chloro-o-orcylidene tetra-acetate* which crystallised from alcohol in needles (1·2 g.), m. p. 115—116°, with a negative ferric reaction [Found: C, 51·4; H, 4·8; OAc, 51·5. $C_8H_5Cl(OAc)_4$ requires C, 51·6; H, 4·6; OAc, 46·2%].

6-Chloro-o-orsellinic Acid (V; R = CO_2H).—2N-Aqueous sodium hydroxide (26·8 ml.) was added dropwise to a well-stirred solution of 6-chloro-*o*-orcylaldehyde (4 g.) and methyl chloroformate (6 g.) in acetone (40 ml.) at below 0° and on dilution with water (80 ml.) ½ hr. later the mixture deposited *6-chloro-3:5-dimethoxycarbonyl-o-orcylaldehyde*, forming long needles (5·3 g.), m. p. 138°, from light petroleum (b. p. 60—80°), with a negative ferric reaction (Found: C, 47·9; H, 4·0; Cl, 12·4. $C_{12}H_{11}O_7Cl$ requires C, 47·6; H, 3·7; Cl, 11·7%). This derivative (3 g.) was oxidised in acetone (50 ml.) at 50—55° with a solution of potassium permanganate (4·7 g.) in water (75 ml.), added in portions during 30 min. Clarification of the mixture at 5° with sulphur dioxide and removal of the solvent left an oil which slowly solidified and was then hydrolysed by dissolution in N-aqueous sodium hydroxide (25 ml.) for 30 min. Precipitated by concentrated hydrochloric acid, the resulting *6-chloro-o-orsellinic acid* was purified by means of aqueous sodium hydrogen carbonate and then crystallised from aqueous acetone, forming cream needles (0·7 g.), m. p. 194° (decomp.), with a purple alcoholic ferric reaction (Found: C, 47·5; H, 3·8; Cl, 17·6. $C_8H_7O_4Cl$ requires C, 47·4; H, 3·5; Cl, 17·5%).

Methyl 6-Chloroeverninate (II; R = H).—With an excess of ethereal diazomethane at 0° for 20 min. 6-chloro-*o*-orsellinic acid (0·5 g.) gave *methyl 6-chloroeverninate* which was freed from acidic impurities with sodium hydrogen carbonate and then crystallised from methanol, forming long needles (0·45 g.), m. p. 143—144°, with a violet ferric reaction [Found: C, 52·1; H, 4·8; Cl, 15·9; OMe, 26·2. $C_8H_5O_3Cl(OMe)_3$ requires C, 52·1; H, 4·8; Cl, 15·4; OMe, 26·9%].

Methyl 6-Chloro-4-nitroeverninate (II; R = NO_2).—Nitric acid (*d* 1·4; 0·08 ml.) was added to methyl 6-chloroeverninate (0·1 g.) in acetic acid (10 ml.). After being kept for 50 min. at room temperature the yellow solution was diluted with water (250 ml.), and the precipitate fractionally crystallised from light petroleum (b. p. 40—60°). The less soluble fractions gave *methyl 6-chloro-4-nitroeverninate* in pale yellow prisms (10 mg.), m. p. 86°, $\lambda_{max.}$ (in EtOH) 317 mμ (ε 2390), having a red ferric reaction (Found: C, 44·0; H, 3·5; N, 5·2. $C_{10}H_{10}O_6NCl$ requires C, 43·6; H, 3·7; N, 5·1%).

3-Chloro-p-orsellinic Acid (VI).—A mixture of methyl *p*-orsellinate (1 g.) and ether (30 ml.) at 0° was treated with sulphuryl chloride (0·75 g.) and next day the solvent was evaporated and the residue twice crystallised from methanol (charcoal), giving *methyl 3-chloro-p-orsellinate* in rhombs (0·75 g.), m. p. 120—121°, with an olive green ferric reaction in water (Found: C, 49·5; H, 4·2; OMe, 14·3. $C_8H_6O_3Cl{\cdot}OMe$ requires C, 49·8; H, 4·2; OMe, 14·3%). This ester (0·2 g.) was hydrolysed with 0·5N-aqueous sodium hydroxide (3 ml.) in alcohol (3 ml.) on the steam-bath for 1·5 hr. After the removal of the alcohol in a vacuum, *3-chloro-p-orsellinic acid* was precipitated by 2N-sulphuric acid and crystallised from water (charcoal), forming slender needles (0·15 g.), m. p. 198—199° (decomp.), with a deep blue ferric reaction (Found: C, 47·2; H, 3·7; Cl, 17·4. $C_8H_7O_4Cl$ requires C, 47·4; H, 3·5; Cl, 17·5%). A mixture of this acid and 6-chloro-*o*-orsellinic acid had m. p. 170—180° (decomp.).

Nitric Acid Degradation of Methyl Dechloro-OO-dimethylnornidulinate.—The addition of nitric acid (*d* 1·47; 0·5 ml.) to methyl dechloro-*OO*-dimethylnornidulinate (0·5 g.) in acetic acid (6 ml.) at the room temperature caused a colour change through yellow to red, complete in 10 min., whereupon the solution was poured into water (100 ml.). Collected in ether, the products were washed with water (5 × 20 ml.) and extracted with aqueous sodium hydrogen carbonate (4 × 10 ml.). Acidification of the dark extract with concentrated hydrochloric acid gave a yellow gum which was isolated with ether and fractionally crystallised from methanol. The first fractions contained the chief fission product, methyl 6-chloro-4-nitroeverninate, which formed yellow prisms (100 mg.), m. p. and mixed m. p. 86—87° having the same ultraviolet absorption spectra and ferric reaction as an authentic specimen (Found: N, 5·0; OMe, 22·4%). Later fractions furnished a very small quantity of methyl 6-chloroeverninate, forming prisms, m. p. and mixed m. p. 143—145°, from methanol.

UNIVERSITY OF LIVERPOOL.

[*Received, January 31st*, 1956.]

686. ***Molecular Polarisability.*** ***The*** C–C, C–O, C=O, C–Cl, C–Br, ***and*** C–I ***Link Polarisabilities, and the Conformations of*** cyclo***Pentane, of*** cyclo***Hexyl Chloride, Bromide, and Iodide, and of*** cyclo***Pentanone,*** cyclo***Hexanone,*** cyclo***Hexane*****-1 : 4-***dione, Camphor, Paraldehyde, and Tetrahydrofuran.*

By (Mrs.) C. G. Le Fèvre and R. J. W. Le Fèvre.

A study of the electric double refraction of solutions of *cyclo*pentane and *cyclo*hexane, of various of their ketonic and halogeno-derivatives, and of paraldehyde, tetrahydrofuran, and (±)-camphor leads to the following conclusions: (*a*) the longitudinal and transverse polarisabilities of the C–C link are respectively $0{\cdot}097_9 \times 10^{-23}$ and $0{\cdot}027_3 \times 10^{-23}$ in *cyclo*pentane and $0{\cdot}098_6 \times 10^{-23}$ and $0{\cdot}027_4 \times 10^{-23}$ in *cyclo*hexane; corresponding values for other bonds are b_L^{C-Cl} 0·382, b_T^{C-Cl} 0·185, b_L^{C-Br} 0·530, b_T^{C-Br} 0·270, b_L^{C-I} 0·807, b_T^{C-I} 0·418, $b_L^{C=O}$ 0·236, $b_T^{C=O}$ 0·139, $b_V^{C=O}$ 0·025, b_L^{C-O} 0·081, and b_T^{C-O} 0·039 (all $\times 10^{-23}$ c.c.).

These data are applied in conformational analysis. *cyclo*Pentane appears non-planar with two carbon atoms differently out of the plane of the remaining three. The same skeleton is satisfactory for *cyclo*pentanone, the *cyclo*pentyl halides, and tetrahydrofuran. Preliminary calculations show it to be applicable to camphor. *cyclo*Hexanone has a chair structure. The halogen atoms in *cyclo*hexyl chloride, bromide, and iodide are predominantly equatorial. Solutions of *cyclo*hexane-1 : 4-dione may contain 20% of a boat form in which the CO groups are part of the basal plane of four carbon atoms. Infrared spectra confirm the absence of enolisation in the diketone.

New determinations of the polarisations at infinite dilution in carbon tetrachloride of twelve substances are listed; apparent moments, on the assumption ${}_DP = 1{\cdot}05R_D$, are also given, and compared with results in the literature.

The work recorded in this paper originated as an attempt to ascertain by experiment the polarisability ellipsoid of the C–C link. For reasons already set out [1-6] the longitudinal and the transverse polarisability (b_L^{C-C} and b_T^{C-C} respectively) of this bond cannot be reliably derived from measurements on the simpler non-polar paraffins, and the suitability of *cyclo*hexane as an alternative seemed therefore worth exploration. The project in its development involved the determination of the molar Kerr constants at infinite dilution, ${}_\infty({}_mK_2)$, of some fourteen substances, mainly halogeno- and keto-derivatives of *cyclo*pentane and *cyclo*hexane, and provided evidence on the conformations of several of these.

For brevity, neither definitions of symbols to be used nor expansions of quantities such as θ_1, θ_2, θ_3, etc., will be repeated here—they are given in full in a recent review,[2] and with less detail in refs. 1 and 3—9. Computations of molecular-polarisability ellipsoids from bond ellipsoids have also been illustrated frequently by us [1-9] and therefore need not be explained again.

The C–C *Link in* cyclo*Hexane.*—The observed ${}_\infty({}_mK_2)$ for this hydrocarbon in carbon tetrachloride is $0{\cdot}98_7 \times 10^{-12}$—a value so small that we feel justified in assuming the

[1] Le Fèvre and Le Fèvre, *Chem. and Ind.*, 1955, 1121.
[2] *Idem*, *Rev. Pure Appl. Chem.*, 1955, **5**, 261.
[3] Le Fèvre, Le Fèvre, and Rao, *J.*, 1956, 708.
[4] Le Fèvre and Le Fèvre, *Chem. and Ind.*, 1955, 506.
[5] Le Fèvre, Presidential Address to Section B, A.N.Z.A.A.S., Melbourne, 1955, *Austr. J. Sci.*, 1956, **18**, 39.
[6] Le Fèvre and Le Fèvre, *J.*, 1954, 1577.
[7] *Idem*, *J.*, 1953, 4041.
[8] *Idem*, *J.*, 1955, 1641.
[9] *Idem*, *J.*, 1955, 2750.

absence or insignificance of a distortion term (the θ_2 of ref. 3) and in calculating the polarisability semiaxes of the molecule directly from the relations (1) and (2):

$$_{\infty}(_{m}K_2) = 2\pi N\theta_1/9 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$_{E}P = 4\pi N(b_1 + b_2 + b_3)/9 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For reasons summarised by Hazebroek and Oosterhoff [10] *cyclo*hexane may be taken as existing at ordinary temperatures very largely as chair molecules (I), in which six hydrogen atoms are disposed [11] in an "equatorial" belt, and the six others alternately upwards and downwards so that their C–H bond directions are parallel to the axis running perpendicularly through the planes of carbon atoms **1**, **3**, and **5**, or **2**, **4**, and **6**. The symmetry of model (I) permits the simplification in equations (1) and (2) that $b_1 = b_2$; $_{E}P$ and $_{D}P$ are known respectively from the data of Vogel [12] and Le Fèvre and Narayana Rao;[13] semiaxes therefore follow as $b_1 = b_2 = 1{\cdot}11_7 \times 10^{-23}$ and $b_3 = 0{\cdot}97_5 \times 10^{-23}$.

(I)

These molecular polarisabilities can be rewritten in terms of four link polarisabilities b_L^{C-C}, b_T^{C-C}, b_L^{C-H}, and b_T^{C-H}, the last two of which are known.[1] Appropriate expressions follow. In order to find out what effect a small content of boat forms (II) would have upon the magnitudes of b_L^{C-C} and b_T^{C-C}, relations based on configuration (II) are also included.

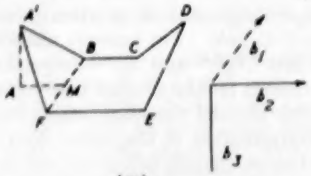
The calculated tensor components are:

(a) *For the chair form of* cyclo*hexane*:

$$\begin{aligned} b_1 = b_2 = {} & 2b_L^{C-C}\cos^2 19^\circ 28'\,(2\cos^2 60^\circ + 1) + 2b_T^{C-C}\,(2\cos^2 30^\circ \\ & + 2\sin^2 19^\circ 28' \,.\, \cos^2 60^\circ + \sin^2 19^\circ 28') + 6b_T^{C-H} + 2b_L^{C-H}\cos^2 19^\circ 28' \\ & + 2b_T^{C-H}\sin^2 19^\circ 28' + 4b_L^{C-H}\cos^2 19^\circ 28' \\ & + 4b_T^{C-H}\sin^2 19^\circ 28' \,.\, \cos^2 60^\circ + 4b_T^{C-H}\cos^2 30^\circ \end{aligned}$$

$$\begin{aligned} b_3 = {} & 6b_L^{C-C}\sin^2 19^\circ 28' + 6b_T^{C-C}\cos^2 19^\circ 28' + 6b_L^{C-H} \\ & + 6b_L^{C-H}\,[\cos^2(\pi - 109^\circ 28')] + 6b_T^{C-H}\sin^2(\pi - 109^\circ 28') \end{aligned}$$

(b) *For the boat form of* cyclo*hexane*:



(II)

(b_1 acts along FB, b_2 along FE)

$$\begin{aligned} b_1 = {} & 2b_T^{C-C} + 4b_L^{C-C}\cos^2 A'FM + 4b_T^{C-C}\sin^2 A'FM + 4b_T^{C-C}\sin^2 A'FA\,.\,\cos^2 AFM \\ & + 4[b_L^{C-H}\sin^2(109^\circ 28'/2) + b_T^{C-H}\cos^2(109^\circ 28'/2)] + 8b_T^{C-H} \end{aligned}$$

$$\begin{aligned} b_2 = {} & 2b_L^{C-C} + 4b_L^{C-C}\cos^2 A'FA\,.\,\cos^2(\pi - AFE) + 4b_T^{C-C}\sin^2(\pi - AFE) \\ & + 4b_T^{C-C}\sin^2 A'FA\,.\,\cos^2(\pi - AFE) + 8(b_L^{C-H}\cos^2 109^\circ 28' \\ & + b_T^{C-H}\sin^2 109^\circ 28') + 2b_L^{C-H} + 2b_L^{C-H}\cos^2(90^\circ - 19^\circ 28') \\ & + 2b_T^{C-H}\sin^2(90^\circ - 19^\circ 28') \end{aligned}$$

$$\begin{aligned} b_3 = {} & 2b_T^{C-C} + 4b_L^{C-C}\sin^2 A'FA + 4b_T^{C-C}\cos^2 A'FA + 4(b_L^{C-H}\cos^2 19^\circ 28' \\ & + b_T^{C-H}\sin^2 19^\circ 28')\cos^2 60^\circ + 4b_T^{C-H}\sin^2 60^\circ + 4b_L^{C-H}\cos^2 19^\circ 28' \\ & + 4b_T^{C-H}\sin^2 19^\circ 28' + 2b_T^{C-H} + 2b_L^{C-H}\cos^2 19^\circ 28' + 2b_T^{C-H}\sin^2 19^\circ 28' \end{aligned}$$

[10] Hazebroek and Oosterhoff, *Discuss. Faraday Soc.*, 1951, **10**, 87.
[11] Hassel, *Quart. Rev.*, 1953, **7**, 221.
[12] Vogel, (*a*) *J.*, 1938, 1323; (*b*) 1948, 1809.
[13] Le Fèvre and Rao, *Austral. J. Chem.*, 1955, **8**, 39.

where A is the projection of A' in the $BCEF$ plane and M the mid-point of BF, and $\cos A'FA = 7^{\frac{1}{2}}/3$, $\cos AFE = -1/7^{\frac{1}{2}}$, and $\cos AFM = (6/7)^{\frac{1}{2}}$.

Accordingly, from (a) we obtain $b_L^{C-C} = 0{\cdot}098_6 \times 10^{-23}$ and $b_T^{C-C} = 0{\cdot}027_4 \times 10^{-23}$, yielding a b_L/b_T ratio of 3·60. Were *cyclo*hexane to contain a low proportion of " boat " forms (Hazebrock and Oosterhoff's paper indicates a possibility of a few units percent.) these figures would scarcely be altered, since from (b), for 100% " boat " forms, b_L^{C-C} and b_T^{C-C} emerge as $0{\cdot}10_9$ and $0{\cdot}02_2 \times 10^{-23}$ respectively.

The present result is thus close to that deduced by Bunn and Daubeny,[14] *viz.*, $b_L^{C-C}/b_T^{C-C} = 3{\cdot}67$, from the refractive indices and density of crystalline hexatriacontane, and differs markedly from estimates, around 90, drawn in the earlier literature from measurements on ethane (cf. refs. 1—5).

The Conformation of cyclo*Pentane.*—An examination of *cyclo*pentane yielded ${}_{\infty}(_{m}K_2) = 0{\cdot}75 \times 10^{-12}$. By setting up the equations appropriate for a *flat* molecule, *viz.* :

$$b_1 = b_2 = b_L^{C-C} + 2b_L^{C-C}(\cos^2 72° + \cos^2 36°) + 2b_T^{C-C}(\cos^2 18° + \cos^2 54°) + 10b_L^{C-H}$$

$$b_3 = 5b_T^{C-C} + 10b_L^{C-H}$$

(noting that $b_L^{C-H} = b_T^{C-H} = b_V^{C-H}$), we obtained a b_L^{C-C}/b_T^{C-C} ratio of 2·52. So marked a change (from 3·60 to 2·52) in this ratio in passing from *cyclo*hexane to *cyclo*pentane seemed *a priori* unlikely. An obvious cause of the discrepancy lay in the configuration adopted : had it been taken as non-planar a larger b_L^{C-C}/b_T^{C-C} ratio would have resulted. Electron-diffraction studies of decafluoro*cyclo*pentane,[15] and spectroscopic measurements [16] and entropy considerations [17-19] with *cyclo*pentane itself, had in fact already raised the possibility that the 5-carbon ring was not flat.

Previous workers [15-19] do not uniformly propose a single structure. *E.g.*, Bastiansen, Hassel, and Lund [15] say that " we have not been able to demonstrate that the five-membered ring must necessarily be non-planar, but it seems rather probable that a deviation from a planar carbon ring is present." They suggest a form in which $C_{(1)}$ is below and $C_{(3)}$ above a plane containing $C_{(2)}$, $C_{(4)}$, and $C_{(5)}$. They remark that " A definitive solution of the problem cannot be given at present based on the electron diffraction method . . . other models may be just as probable." Tschamler and Voetter [16] speak of a slight departure from planarity with *cyclo*pentane but do not specify it. American authors [17-19] favour a C_s configuration with one carbon out of the plane of the other four but do not exclude a form C_2 similar to that discussed by Bastiansen *et al.*

The C_s model is attractive, since it is commonly assumed to occur in natural polycyclic systems (*e.g.*, chloro-, bromo-, and cyano-camphor,[20] in calciferol 4-iodo-5-nitrobenzoate,[21] in ring D of cholesteryl iodide,[22] etc.).

The situation has been assessed by Barker and Stephens [23] thus : planar structures are stabilised by forces tending to retention of tetrahedral angles but repulsions between hydrogens of neighbouring methylene groups are at a maximum in flat models. Repulsions produce torsional forces around the C–C bonds which (cf. Miller and Inskeep [24]) act to pucker the ring. Barker and Stephens consider this puckering to be small so that, with a few exceptions, (spectroscopic) selection rules for a planar ring can be followed. At the outset there was therefore no evidence enabling us to choose between the C_s and the C_2 configuration for *cyclo*pentane, although we slightly preferred the latter since it appeared to offer the better mutual accommodation for the hydrogen atoms.

[14] Bunn and Daubeny, *Trans. Faraday Soc.*, 1954, **50**, 1173.
[15] Bastiansen, Hassel, and Lund, *Acta Chem. Scand.*, 1949, **3**, 297.
[16] Tschamler and Voetter, *Monatsh.*, 1952, **83**, 302, 835, 1228.
[17] Aston, Schumann, Fink, and Doty, *J. Amer. Chem. Soc.*, 1941, **63**, 2039.
[18] Kilpatrick, Pitzer, and Spitzer, *ibid.*, 1947, **69**, 2483.
[19] Aston, Fink, and Schumann, *ibid.*, 1943, **65**, 341.
[20] Wiebenga and Krom, *Rec. Trav. chim.*, 1946, **65**, 663.
[21] Crowfoot and Dunitz, *Nature*, 1948, **162**, 608.
[22] Carlisle and Crowfoot, *Proc. Roy. Soc.*, 1945, *A*, **184**, 64.
[23] Barker and Stephens, *J.*, 1954, 4550.
[24] Miller and Inskeep, *J. Chem. Phys.*, 1950, **18**, 1519.

A different approach was then made. The molar Kerr constants of *cyclo*pentyl chloride, bromide, and iodide, of *cyclo*pentanone, and of tetrahydrofuran were ascertained as follows:

	$10^{12}\ {}_{\infty}(_mK_2)$		$10^{12}\ {}_{\infty}(_mK_2)$
*cyclo*Pentyl chloride	59·3	*cyclo*Pentanone	147·6
" bromide	96·8	Tetrahydrofuran	−2·4
" iodide	153·4		

At first glance the most significant of these results is that of tetrahydrofuran which in no circumstances could be planar and have a negative Kerr constant. In fact, if we may anticipate knowledge of the polarisabilities of the C–O link, a planar configuration should, by adopting the C–O–C angle reported by Allen and Sutton,[25] have ${}_mK$ nearly $+30 \times 10^{-12}$.

For the quantitative analysis of these data we have made three assumptions: that the b_L^{C-C}/b_T^{C-C} ratio should be the same in 5- as in 6-membered rings, that the *cyclo*pentane skeleton persists unaltered in derivatives of this hydrocarbon, and that with polar solutes θ_1 may be neglected, so that ${}_{\infty}(_mK_2) \sim 2\pi\mathbf{N}\theta_2/9$ (numerical data justifying the last approximation have been given earlier [6,9]). Then, when the molecular resultant moment μ lies along b_1 we may write:

$$\theta_2 = \mu^2(2b_1 - b_2 - b_3)/45k^2T^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

whence the quantity $(2b_1 - b_2 - b_3)$ is directly obtainable. Now if b_1', b_2', and b_3' are the polarisabilities of *cyclo*pentane such that b_1' is in the direction of $\mu_{resultant}$ in *cyclo*pentanone, *i.e.*, along MA in (V), then, writing b^{cp} to refer to *cyclo*pentanone, we have:

$$b_1^{cp} = b_1' + b_L^{C=O} - 2b_L^{C-H}$$
$$b_2^{cp} = b_2' + b_T^{C=O} - 2b_L^{C-H}$$
$$b_3^{cp} = b_3' + b_V^{C=O} - 2b_L^{C-H}$$

whence
$$2b_1 - b_2 - b_3 = 2b_1' - b_2' - b_3' + 2b_L^{C=O} - b_T^{C=O} - b_V^{C=O}$$
$$= 2b_1' - b_1' - b_3' + 3b_L^{C=O} - b_{Tot}^{C=O}$$

(where $b_{Tot}^{C=O}$ signifies the total of the longitudinal and two transverse polarisabilities of the C=O bond—it can be calculated from link refractivities).

Similarly for the *cyclo*pentyl halides the molecular semi-axes are:

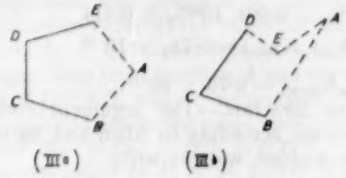
$$b_1 = b_1' \cos^2 109° 28'/2 + b_3' \sin^2 109° 28'/2 + b_L^{C-Hal} - b_L^{C-H}$$
$$b_2 = b_2' + b_T^{C-Hal} - b_L^{C-H}$$
$$b_3 = b_2' \cos^2 109° 28'/2 + b_1' \sin^2 109° 28'/2 + b_T^{C-Hal} - b_L^{C-H}$$

Using a b_L^{C-C}/b_T^{C-C} ratio of 3·6, we next proceeded to calculate for *cyclo*pentane itself values b_1', b_2', and b_3' for its tensor ellipsoid. These, in addition to yielding the observed ${}_mK$ for *cyclo*pentane, had other requirements imposed on them: (1) They had to represent the three principal polarisabilities of a stereochemical conformation which might reasonably be expected to exist. (2) They had, when substituted into the expression for $2b_1 - b_2 - b_3$ for *cyclo*pentanone, to yield a value for this term from which $({}_mK)_{calc.}$ for the compound could be derived and found to be in accordance with $({}_mK)_{expt.}$. (3) They had, when inserted into $2b_1 - b_2 - b_3$ for *cyclo*pentyl halides, to give figures for b_L^{C-Hal} and b_T^{C-Hal} which when used in calculating ${}_mK$ for the *cyclo*hexyl halides produced results in agreement with $({}_mK)_{expt.}$. (4) They had to represent the principal polarisabilities of a stereochemical structure on which, with appropriate modifications, we could explain the negativity of ${}_mK$ for tetrahydrofuran.

As already stated, there appeared to be two possible conformations, (III*a* and *b*) in which respectively four and three carbon atoms lie in one plane. Only the second of these (III*b*), by the criterion outlined above, satisfied all our results. Its generation can be credibly viewed as follows: initially let the five carbons be disposed as in *cyclo*hexane

[25] Allan and Sutton, *Acta Cryst.*, 1950, **3**, 46.

(see IV), with tetrahedral angles at *E*, *A*, and *B*; then *D* and *C* would be separated by a distance 2 × (C–C bond length) sin (109° 28′/2), whereas in fact [18,25] the distance is 1·54 Å. With a model it is found that this distance can be achieved by altering the angles at *A*, *B*, and *E* by a concertina-like movement thus retaining as much staggering as possible

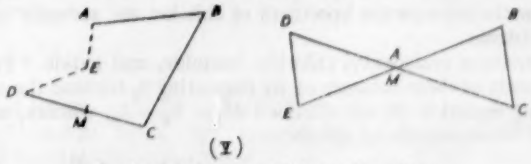


(III*a*) (III*b*) (IV)

Four carbons in one plane. Three carbons in one plane.

of all the adjacent C–H links; it becomes also obvious that *C* and *D* cannot both lie in the same plane as *B* and *E*.

We think that ideally the correct (single) conformation should be that which affords uniform mutual repulsion of C–H bonds; however, being unable to calculate this, *a priori*, by trial and error we have evolved the structure (V). This is applicable to all the 5-membered rings studied in this paper. With reference to (V) it is specified as follows: If *X*, *M*, and *Y* are the midpoints of *DE*, *CD*, and *BC* respectively, then *A*, *X*, *M*, and *Y* lie on one plane. The projections of *B*, *C*, *D*, and *E* on this plane are at *B*′, *C*′, *D*′, and *E*′, where $BB' = CC' = DD' = EE' = 0{\cdot}32$ Å. The angles at *A*, *C*, and *D* are, in order, 111°, 108°, and 108°, and the C–C distance 1·54 Å. Then *AB* and *AE* lie at an angle *R* to the horizontal (*AXMY* plane), where $R = 12° 1'$; and *CD*, *BC*, and *DE* lie at an angle *S* to the horizontal



(V)

Conformation proposed for *cyclo*pentane.

where $S = 24° 36'$. Angle *P* is the projection of ∠*BCD* on *B*′*CD*′ in the horizontal plane minus 90°, $\angle P = 35° 40'$; $\angle Q$ is $B'AE'/2 = 54° 38'$ where *B*′*AE*′ is the projection of ∠*BAE* in the horizontal plane.

Appropriate expressions for the semiaxes of the polarisability ellipsoid are (b_1 along *XY*, b_2 along *MA*):

$$\begin{aligned} b_1 = {} & b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \cos^2 24° 36' + b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \sin^2 24° 36' && \text{(for } C\text{–}D\text{)} \\ & + 2b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \cos^2 12° 1' \,.\, \sin^2 Q + 2b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \cos^2 Q + 2b_{\mathrm{V}}^{\mathrm{C\text{-}C}} \sin^2 12° 1' \,.\, \sin^2 Q \\ & && \text{(for } A\text{–}B \text{ and } A\text{–}E\text{)} \\ & + 2b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \cos^2 24° 36' \,.\, \sin^2 P + 2b_{\mathrm{V}}^{\mathrm{C\text{-}C}} \sin^2 24° 36' \,.\, \sin^2 P + 2b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \cos^2 P \\ & && \text{(for } B\text{–}C \text{ and } D\text{–}E\text{)} \\ & + 10b_{\mathrm{L}}^{\mathrm{C\text{-}H}} \end{aligned}$$

$$\begin{aligned} b_2 = {} & b_{\mathrm{T}}^{\mathrm{C\text{-}C}} && \text{(for } C\text{–}D\text{)} \\ & + 2b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \cos^2 12° 1' \,.\, \cos^2 Q + 2b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \sin^2 Q + 2b_{\mathrm{V}}^{\mathrm{C\text{-}C}} \sin^2 12° 1' \,.\, \cos^2 Q \\ & && \text{(for } A\text{–}B \text{ and } A\text{–}E\text{)} \\ & + 2b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \cos^2 24° 36' \,.\, \cos^2 P + 2b_{\mathrm{V}}^{\mathrm{C\text{-}C}} \sin^2 24° 36' \,.\, \cos^2 P + 2b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \sin^2 P \\ & && \text{(for } B\text{–}C \text{ and } D\text{–}E\text{)} \\ & + 10b_{\mathrm{L}}^{\mathrm{C\text{-}H}} \end{aligned}$$

$$\begin{aligned} b_3 = {} & 2b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \sin^2 12° 1' + 2b_{\mathrm{V}}^{\mathrm{C\text{-}C}} \cos^2 12° 1' && \text{(for } A\text{–}B \text{ and } A\text{–}E\text{)} \\ & + 2b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \sin^2 24° 36' + 2b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \cos^2 24° 36' && \text{(for } B\text{–}C \text{ and } D\text{–}E\text{)} \\ & + b_{\mathrm{L}}^{\mathrm{C\text{-}C}} \sin^2 24° 36' + b_{\mathrm{T}}^{\mathrm{C\text{-}C}} \cos^2 24° 36' && \text{(for } C\text{–}D\text{)} \\ & + 10b_{\mathrm{L}}^{\mathrm{C\text{-}H}} \end{aligned}$$

From refractivity data, $b_{T,A}^{C-C}$ appears as $0{\cdot}153_3$ and $0{\cdot}152_3 \times 10^{-23}$ respectively in *cyclo*hexane and *cyclo*pentane. Accordingly, with a b_L^{C-C}/b_T^{C-C} ratio of 3·60, $b_T^{C-C} = 0{\cdot}097_9 \times 10^{-23}$ and $b_T^{C-C} = 0{\cdot}027_2 \times 10^{-23}$ for the C–C bond in 5-membered rings. Therefore, for *cyclo*pentane we have:

$$10^{23}b_1 = 0{\cdot}962,\ 10^{23}b_2 = 0{\cdot}891,\ 10^{23}b_3 = 0{\cdot}814,$$
$$10^{35}\theta_1 = 0{\cdot}178, \text{ and } {}_\infty(_mK)_{calc.} = 0{\cdot}74_9 \times 10^{-12}.$$

The last figure compares well with ${}_\infty(_mK)_{expt.} = 0{\cdot}75 \times 10^{-12}$.

Verification of Proposed cyclo*Pentane Structure.*—The argument concerning *cyclo*pentanone will be set out first. For acetone, according to Allen and Sutton's list,[25] the C–C–O angle is 123°; using b^{ac} to refer to acetone, we may write:

$$b_1^{ac} = b_L^{C=O} + 2b_L^{C-C}\cos^2 57° + 2b_T^{C-C}\sin^2 57° + 6b_L^{C-H}$$
$$b_2^{ac} = b_T^{C=O} + 2b_L^{C-C}\sin^2 57° + 2b_T^{C-C}\cos^2 57° + 6b_L^{C-H}$$
$$b_3^{ac} = b_V^{C=O} + 2b_T^{C-C} + 6b_L^{C-H}$$

We [7] found ${}_\infty(_mK_2)^{ac}$ to be 101×10^{-12}, whence $\theta_1 + \theta_2 = 24{\cdot}0 \times 10^{-35}$. As a near approximation let $\theta_1 = 1 \times 10^{-35}$, then $\theta_2 = 2{\cdot}3 \times 10^{-34}$. By use of equation (3), and with $b_{Tot}^{C=O}$ in acetone $= 0{\cdot}394 \times 10^{-23}$, $b_L^{C=O}$ emerges as $0{\cdot}230 \times 10^{-23}$. If now in the expressions giving b_1, b_2, and b_3 for *cyclo*pentanone, as set out above, we write the values previously calculated for b_1, b_2, and b_3 of *cyclo*pentane, and adopt $b_L^{C=O} = 0{\cdot}230 \times 10^{-12}$, then θ_2^{cp} may be computed as $33{\cdot}8 \times 10^{-35}$, which is in good agreement with $(\theta_1 + \theta_2)_{expt.} = 35{\cdot}11 \times 10^{-35}$; or, if we transform to molar Kerr constants and assume $\theta_1^{cp} = 1 \times 10^{-35}$, we have $(_mK)_{calc.} = 146{\cdot}3 \times 10^{-12}$ against $(_mK)_{expt.} = 147{\cdot}6 \times 10^{-12}$.

No precise stereostructure for *cyclo*pentanone seems to have been given before. Erlandsson,[26] from the micro-wave spectrum of this ketone, recently concluded that the carbon ring is non-planar.

Another test involves *cyclo*pentyl chloride, bromide, and iodide. From the measured ${}_\infty(_mK_2)$'s and moments of these substances, by neglecting θ_1 because the μ's involved are not small, and by using equation (3) we obtained $2b_1 - b_2 - b_3$, whence, using configuration (V), b_L^{C-Hal} and b_T^{C-Hal} were deduced as follows:

	C–Cl	C–Br	C–I
$10^{23}b_L$	0·382	0·530	0·807
$10^{23}b_T$	0·185	0·270	0·418

We assumed that the last quantities were likely to be the same in 5- as in 6-membered rings. By insertion in the expression for b_1, b_2, and b_3 for the "equatorial" and the "axial" conformations of each of the *cyclo*hexyl halides, θ_1 and θ_2 and hence the ${}_mK$'s were computed.

The relations applicable are (where b^{ch} refer to *cyclo*hexanone):

For the "equatorial" halides:

$$b_1 = b_L^{C-Hal} + b_1^{ch}\cos^2 19° 28' + b_3^{ch}\sin^2 19° 28' - b_L^{C-H}$$
$$b_2 = b_T^{C-Hal} + b_2^{ch} - b_L^{C-H}$$
$$b_3 = b_T^{C-Hal} + b_3^{ch}\cos^2 19° 28' + b_1^{ch}\sin^2 19° 28' - b_L^{C-H}$$

For the "axial" halides:

$$b_1 = b_L^{C-Hal} + b_3^{ch} - b_L^{C-H}$$
$$b_2 = b_3 = b_L^{C-Hal} + b_1^{ch} - b_L^{C-H}$$

The results expressed as molar Kerr constants are:

*cyclo*Hexyl halide	$10^{12}\ {}_mK_{calc.}$ Equatorial confn.	$10^{12}\ {}_mK_{calc.}$ Axial confn.	$10^{12}\ {}_mK_{expt.}$
Chloride	130	42	122
Bromide	179	82	181
Iodide	246	152	249

[26] Erlandsson, *J. Chem. Phys.*, 1954, **22**, 563.

The equatorial conformations of these halides are thus unambiguously indicated. Such would not be the case had the molecular ellipsoid for *cyclo*pentane been seriously in error. The conclusion is in harmony with other work reviewed by Hassel.[11]

The Conformation of Tetrahydrofuran.—It next became of interest to know whether the model for *cyclo*pentane was applicable to other 5-membered ring molecules. Tetrahydrofuran was therefore considered, the following dimensions (Allen and Sutton [25]) being used: C–O distance 1·43 Å; C–C distance 1·54 Å; angle C–O–C 111° ± 2°. On the basis of form (V) let the oxygen atom lie at position A and the carbon atoms be at B, C, D, and E; take the mid-points of DE, CD, and BC respectively as X, M, and Y, and regard the $AXMY$ plane as horizontal, and denote the projections of B, C, D, and E on to this plane as B', C', D', and E' where $BB' = CC' = DD' = 0{\cdot}32$ Å. The angles at A, C, and D are 111° ± 2° while those corresponding to R, S, P, and Q in *cyclo*pentane emerge, in order, as 12° 57′, 24° 36′, 43° 2′, and 55°. Then, putting b_1 along the direction of $\mu_{\text{resultant}}$, *i.e.*, along MA, and b_2 along XY, we have (writing b^{tf} to refer to tetrahydrofuran):

$$\begin{aligned} b_1^{\text{tf}} = {} & b_{\text{T}}^{\text{C-C}} \qquad \text{(for } C\text{–}D\text{)} \\ & + 2b_{\text{L}}^{\text{C-O}}\cos^2 12^\circ 57' \,.\, \cos^2 Q + 2b_{\text{T}}^{\text{C-O}}\sin^2 Q + 2b_{\text{L}}^{\text{C-O}}\sin 12^\circ 57' \,.\, \cos^2 Q \\ & \qquad\qquad \text{(for } A\text{–}B \text{ and } A\text{–}E\text{)} \\ & + 2b_{\text{L}}^{\text{C-C}}\cos^2 24^\circ 36' \,.\, \cos^2 P + 2b_{\text{T}}^{\text{C-C}}\sin^2 24^\circ 36' \,.\, \cos^2 P + 2b_{\text{T}}^{\text{C-C}}\sin^2 P \\ & \qquad\qquad \text{(for } B\text{–}C \text{ and } D\text{–}E\text{)} \\ & + 8b_{\text{L}}^{\text{C-H}} \end{aligned}$$

$$\begin{aligned} b_2^{\text{tf}} = {} & b_{\text{L}}^{\text{C-C}}\cos^2 24^\circ 36' + b_{\text{T}}^{\text{C-C}}\sin^2 24^\circ 36' \qquad \text{(for } C\text{–}D\text{)} \\ & + 2b_{\text{L}}^{\text{C-O}}\cos^2 12^\circ 57' \,.\, \sin^2 Q + 2b_{\text{T}}^{\text{C-O}}\cos^2 Q + 2b_{\text{L}}^{\text{C-O}}\sin^2 12^\circ 57' \,.\, \sin^2 Q \\ & \qquad\qquad \text{(for } A\text{–}B \text{ and } A\text{–}E\text{)} \\ & + 2b_{\text{L}}^{\text{C-C}}\cos^2 24^\circ 36' \,.\, \sin^2 P + 2b_{\text{T}}^{\text{C-C}}\sin^2 24^\circ 36' \,.\, \sin^2 P + 2b_{\text{T}}^{\text{C-C}}\cos^2 P \\ & \qquad\qquad \text{(for } B\text{–}C \text{ and } C\text{–}E\text{)} \\ & + 8b_{\text{L}}^{\text{C-H}} \end{aligned}$$

$$\begin{aligned} b_3^{\text{tf}} = {} & 2b_{\text{L}}^{\text{C-O}}\sin^2 12^\circ 57' + 2b_{\text{T}}^{\text{C-O}}\cos^2 12^\circ 57' \qquad \text{(for } A\text{–}B \text{ and } A\text{–}E\text{)} \\ & + 2b_{\text{L}}^{\text{C-C}}\sin^2 24^\circ 36' + 2b_{\text{T}}^{\text{C-C}}\cos^2 24^\circ 36' \qquad \text{(for } B\text{–}C \text{ and } D\text{–}E\text{)} \\ & + b_{\text{L}}^{\text{C-C}}\sin^2 24^\circ 36' + b_{\text{T}}^{\text{C-C}}\cos^2 24^\circ 36' \qquad \text{(for } C\text{–}D\text{)} \\ & + 8b_{\text{L}}^{\text{C-H}} \end{aligned}$$

Adopting the same $b_{\text{L}}^{\text{C-C}}$ and $b_{\text{T}}^{\text{C-C}}$ values as for *cyclo*pentane, and using a $b_{\text{L}}^{\text{C-O}}/b_{\text{T}}^{\text{C-O}}$ ratio of 2·08 (derived from ${}_mK$ for paraldehyde as discussed below), together with $\mu_{\text{expt.}} = 1{\cdot}81$ D, yields:

$$10^{23}b_1 = 0{\cdot}759, \qquad 10^{23}b_2 = 0{\cdot}836, \qquad 10^{23}b_3 = 0{\cdot}706$$

whence

$$\theta_1 + \theta_2 = -0{\cdot}54 \times 10^{-35}$$

and ${}_mK_{\text{calc.}} = -2{\cdot}27 \times 10^{-12}$, compared with ${}_\infty({}_mK_2)_{\text{expt.}} = -2{\cdot}4 \times 10^{-12}$.

Agreement between prediction and measurement is satisfactory. It may be remarked that the alternative model, analogous to the C_s form of *cyclo*pentane, requires for a negative Kerr constant a considerable interplanar angle; although such folding may be forced in rigid polycyclic molecules, *e.g.*, cantharidin, it is quite credible that it cannot be held in single, and therefore more flexible, ring systems. It is relevant that Tschamler and Voetter,[16] from Raman and infrared spectral data, could only conclude that tetrahydrofuran had pseudo-symmetry D_{5h}, *i.e.*, that the ring was not completely flat (a similarly qualitative opinion had been reported by Beach [27] in 1941); on the other hand, tetrahydrothiophen was recognised [16] as probably having symmetry C_2, *i.e.*, symmetry of the type here allotted to tetrahydrofuran.

Derivation of $b_{\text{L}}^{\text{C-O}}$ *and* $b_{\text{T}}^{\text{C-O}}$.—In paraldehyde it is considered that the three methyl

[27] Beach, quoted as "private communication" by Aston *et al.*, *J. Amer. Chem. Soc.*, 1941, **63**, 2030.

groups are disposed equatorially.[28-33] Allen and Sutton [25] list C–O and C–C separations of 1·43 and 1·54 Å. The molecular skeleton, by analogy with trioxan,[34,35] and by relationship with dioxan,[36,37] is a " staggered " or chair structure. On these premises, putting b_1 in the direction of $\mu_{resultant}$, we may write :

$$b_1 = 6b_L^{C\text{-}O} \sin^2 19° 28' + 6b_T^{C\text{-}O} \cos^2 19° 28' + 3b_L^{C\text{-}H} + 3[b_L^{C\text{-}C} \cos^2 (90 - 19° 28')] + 3b_T^{C\text{-}C} \cos^2 19° 28' + 9b_L^{C\text{-}H}$$

and $b_2 = b_3 = 2b_L^{C\text{-}O} \cos^2 19° 28' . (2\cos^2 60° + 1) + 2b_T^{C\text{-}O} (2\cos^2 30° + 2\sin^2 19° 28' . \cos^2 60° + \sin^2 19° 28') + 12b_L^{C\text{-}H} + b_L^{C\text{-}C} \cos^2 19° 28' + b_T^{C\text{-}O} \sin^2 19° 28' + 2(b_L^{C\text{-}C} \cos^2 19° 28' . \cos 60° + b_T^{C\text{-}O} \sin 19° 28' . \cos 60° + b_T^{C\text{-}O} \cos 30°)$

In carbon tetrachloride, ${}_\infty({}_mK_2)$ for paraldehyde is now found to be $-57·0 \times 10^{-12}$, whence, with ${}_RP = 31·70$ c.c. and $\mu = 1·98$ D, $10^{23}b_1 = 1·162$ and $10^{23}b_2 = 10^{23}b_3 = 1·292$. Solution of the above equations then gives :

$$10^{23}b_L^{C\text{-}O} = 0·081,\ 10^{23}b_T^{C\text{-}O} = 0·039, \text{ and } b_L^{C\text{-}O}/b_T^{C\text{-}O} = 2·08$$

In these calculations we have assumed the " chair " angles to be tetrahedral. Small deviations from this value do not appreciably affect the $b_L^{C\text{-}O}/b_T^{C\text{-}O}$ ratio. Further, if expressions for b_1, b_2, and b_3 be set up for a paraldehyde structure in which the methyl groups are axially disposed, then computation along the lines just set out produces a $b_L^{C\text{-}O}/b_T^{C\text{-}O}$ ratio of approximately 1 : 2. Such a result, which is highly unlikely, can be regarded as further evidence for the equatorial disposition of the three methyl groups.

Conformation of cyclo*Hexanone.*—Results already mentioned in this paper allow *a priori* calculations to be made of ${}_\infty({}_mK_2)$ for *cyclo*hexanone in its boat and chair conformations; $b_L^{C=O} = 0·230 \times 10^{-23}$ is derived from acetone. We have for the chair form :

$$b_1^{ch} = b_1^{ch} \sin^2 (109° 28'/2) + b_3^{ch} \cos^2 (109° 28'/2) + b_L^{C=O} - 2b_L^{C\text{-}H}$$
$$b_2^{ch} = b_2^{ch} + b_T^{C=O} - 2b_L^{C\text{-}H}$$
$$b_3^{ch} = b_3^{ch} \sin^2 (109° 28'/2) + b_1^{ch} \cos^2 (109° 28'/2) + b_V^{C=O} - 2b_L^{C\text{-}H}$$

and for the boat form :

$$b_1^{ch} = b_L^{C=O} + b_2^{ch} \cos^2 (109° 28'/2) + b_3^{ch} \sin^2 (109° 28'/2) - 2b_L^{C\text{-}H}$$
$$b_2^{ch} = b_T^{C=O} + b_1^{ch} - 2b_L^{C\text{-}H}$$
$$b_3^{ch} = b_V^{C=O} + b_2^{ch} \sin^2 (109° 28'/2) + b_3^{ch} \cos^2 (109° 28'/2) - 2b_L^{C\text{-}H}]$$

From these equations we deduce molar Kerr constants for the two forms as follow :

$$\text{Chair, } {}_mK_{calc.} = 178 \times 10^{-12} \qquad \text{Boat, } {}_mK_{calc.} = 54 \times 10^{-12}$$

The observed ${}_\infty({}_mK_2)$ being 183×10^{-12}, we conclude that *cyclo*hexanone under our conditions exists in the chair form.

Conformation of cyclo*Hexane*-1 : 4-*dione.*—This substance has been studied in benzene, because of its sparing solubility in carbon tetrachloride; its ${}_\infty({}_mK_2)$ is $-41·2 \times 10^{-12}$.

[28] Ackerman and Mayer, *J. Chem. Phys.*, 1936, **4**, 377.
[29] Brockway and Carpenter, *J. Amer. Chem. Soc.*, 1936, **58**, 1270.
[30] Gerding *et al.*, *Rec. Trav. chim.*, 1939, **58**, 604, 614; 1941, **60**, 258.
[31] Calderbank and Le Fèvre, *J.*, 1949, 199.
[32] Le Fèvre, Mulley, and Smythe, *J.*, 1950, 290.
[33] Saksena, *Proc. Indian Acad. Sci.*, 1940, **12**, *A*, 321.
[34] Moerman, *Rec. Trav. chim.*, 1937, **56**, 161.
[35] Moerman and Wiebenga, *Z. Krist.*, 1937, **97**, 323.
[36] Hassel and Viervoll, *Acta Chem. Scand.*, 1947, **1**, 149.
[37] Brockway and Sutton, *J. Amer. Chem. Soc.*, 1936, **57**, 473.

Older evidence [38] for non-enolisation has now been supplemented by infrared spectral data (see Experimental section) which confirm this conclusion. In the absence of enol forms, negativity of ${}_mK$ must be due to the presence of one or more boat conformations.

Accordingly we set up the expressions for b_1, b_2, and b_3, of the three possible configurations indicated in (VI).

(VI)

For the chair form A we have:

$$b_1 = 2b_L^{C=O} + b_1^{ch}\sin^2(109°\,28'/2) + b_3^{ch}\cos^2(109°\,28'/2) - 4b_L^{C-H}$$
$$b_2 = 2b_L^{C=O} + b_1^{ch} - 4b_L^{C-H}$$
$$b_3 = 2b_V^{C=O} + b_1^{ch}\cos^2(109°\,28'/2) + b_3^{ch}\sin^2(109°\,28'/2) - 4b_L^{C-H}$$

For the boat form B we have :

$$b_1 = b_3^{ch} - 4b_L^{C-H} + 2b_L^{C=O}\sin^2(109°\,28'/2) + 2b_V^{C=O}\cos^2(109°\,28'/2)$$
$$b_2 = b_2^{ch} - 4b_L^{C-H} + 2b_L^{C=O}\cos^2(109°\,28'/2) + 2b_V^{C=O}\sin^2(109°\,28'/2)$$
$$b_3 = b_1^{ch} - 4b_L^{C-H} + 2b_T^{C=O}$$

(In this computation and those following, polarisabilities written as b_1^{ch}, b_2^{ch}, and b_3^{ch} are those appropriate for the boat conformation.) For the boat form C we must first refer to (VII). Let $ABCDEF$ be the skeleton structure of this form ($AB = l$); the C=O links at C and F lie in the $ABCD$ and the $ADEF$ plane respectively. A' lies on AD and is the projection of A perpendicular to BF. Then $AFA' = 19°\,28'$. Because μ at F bisects the angle AFE, $\angle A'FK = 109°\,28'/2 - 19°\,28'$; therefore μ at F makes an angle $109°\,28'/2$ with DA; $FA' = l\cos 19°\,28'$, and $FA'' = l\sin 109°\,28'/2$ (where A'' is the projection of A' on to BF); then $\angle FA'A'' = 60°$, and $\angle FA'B = 120°$.

Accordingly, taking b_1 along $\mu_{resultant}$ we have :

$$b_1 = b_3^{ch} + 2b_L^{C=O}\sin^2 109°\,28' \,.\, \cos^2 60° + 2b_V^{C=O}\sin^2 60° + 2b_T^{C=O}\cos^2(109°\,28'/2)\cos^2 60° - 4b_L^{C-H}$$
$$b_2 = 2b_L^{C=O}\cos^2(90° - \phi) + 2b_V^{C=O}\sin^2(90° - \phi) + b_1^{ch}\cos^2\omega + b_2^{ch}\sin^2\omega - 4b_L^{C-H}$$

where $$\cos^2\omega = \cos^2(109°\,28'/2)\cos^2(90° - \phi),$$

and $$\cos\phi = \sin(109°\,28'/2) \,.\, \cos 60° = 65°\,54'$$

$$b_3 = 2b_T^{C=O} + b_1^{ch}\sin^2\omega + b_2^{ch}\cos^2\omega - 4b_L^{C-H}$$

Resultant moments are calculated for models (A), (B), and (C) by using $\mu^{C=O} = 3{\cdot}14$ D (as in *cyclo*hexanone). In order to avoid an accumulated error in $b_L^{C=O}$, we redetermined this value directly from ${}_mK$ for *cyclo*hexanone, following the procedure previously discussed for obtaining b_L^{C-Hal} and b_T^{C-Hal} from *cyclo*pentyl halides. We thus found $b_L^{C=O} = 0{\cdot}236 \times 10^{-23}$ and $b_V^{C=O} + b_T^{C=O} = 0{\cdot}164 \times 10^{-23}$. Substituting for $b_L^{C=O}$ in the expanded $\theta_1 + \theta_2$ term gives $b_V^{C=O} = 0{\cdot}025 \times 10^{-23}$ and $b_T^{C=O} = 0{\cdot}139 \times 10^{-23}$. These values and $\mu_{resultant}$ for (B) and (C) can only be regarded as near estimates because of their mode of derivation.

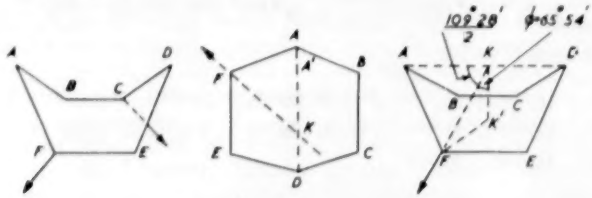
[38] Le Fèvre and Le Fèvre, *J.*, 1935, 1696.

Our final calculations in comparison with experiment are :

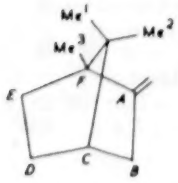
Configuration	$10^{12}\ (_mK)_{calc.}$	$10^{12}\ (_mK)_{expt.}$
(*A*)	7·6	−41·2
(*B*)	16·8	
(*C*)	−233	

The results are in conformity with a 20% mixture of (*C*) and 80% of (*A*). Incidentally, the observed dipole moment, 1·2 D, can reasonably be shown to correspond with 21% of (*C*) and 79% of (*A*). Such excellent agreement between two different methods we regard as fortuitous.

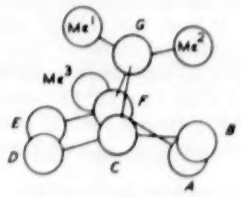
It is interesting that in conformation (*C*) the two C=O dipoles are situated in those positions that allow maximum staggering of the adjacent C–H bonds in the molecule. Conformation (*B*) does not permit this. Our conclusions thus support ideas that in saturated cyclic hydrocarbons mutual repulsions between C–H links are the dominant factors determining configuration. Although form (*C*) is not that discussed [38] by us in 1935, the fact remains that *cyclo*hexane-1 : 4-dione is still the only example of a monocyclic *cyclo*hexane derivative whose existence in a boat conformation has been detected by experiment (cf. Hassel [11]).



(VII)



(VIII)



(IX)

Conformation of Camphor.—Bredt's classical formula for this ketone, (VIII), contains two fused non-planar 5-rings. It is therefore of interest to explore the applicability of our *cyclo*pentane conformation to such a case.

$_{\infty}(_mK_2)$ of (±)-camphor is 115×10^{-12}. Let θ_1 be approx. 1×10^{-35}, then $\theta_2 = 2{\cdot}64 \times 10^{-34}$; and since $\mu = 3{\cdot}1_1$ D, $2b_1 - b_2 - b_3 = 0{\cdot}208 \times 10^{-23}$. Because $b_1 + b_2 + b_3 = 5{\cdot}201 \times 10^{-23}$ (from refractivity), b_1 emerges as $1{\cdot}80_3 \times 10^{-23}$ and $(b_2 + b_3)$ as $3{\cdot}39_8 \times 10^{-23}$. Since b_1 lies along $\mu_{resultant}$ we can write (using b^{cam} to refer to camphor, and b^{sk} to refer to the carbon skeleton) :

$$b_1^{cam} = b_1^{sk} + \tfrac{1}{3}b_{Tot}^{C-H} + b_L^{C=O}$$

$$(b_2 + b_3)^{cam} = (b_2 + b_3)^{sk} + \tfrac{2}{3}b_{Tot}^{C-H} + b_T^{C=O} + b_V^{C=O}$$

If we adopt $b_L^{C=O} = 0{\cdot}230 \times 10^{-23}$, as in *cyclo*pentanone, and $b_{Tot}^{C=O} = 0{\cdot}432 \times 10^{-23}$ (obtained from $b_1 + b_2 + b_3$ for camphor, *viz.*, $5{\cdot}201 \times 10^{-23}$. This, equals $8b_{Tot}^{C-C}$, as in 5-membered rings, plus $3b_{Tot}^{C-C}$ as in propane, plus $16b_{Tot}^{C-H}$, plus $b_{Tot}^{C=O}$) then $b_1^{sk} = 1{\cdot}57_3 \times 10^{-23}$ and $(b_2 + b_3)^{sk} = 3{\cdot}19_6 \times 10^{-23}$.

We shall now attempt, so far as available data make possible, to compute the ellipsoid of the skeleton. In Model (IX) let the C=O dipole act at *A*, the *gem.*-dimethyl group lie at *G*, and the other methyl group at *F*. Let *M*, *X*, *Y*, and *Z* be the mid-points of *CG*, *BC*, *GF*, and *EF*. In the five-membered ring *ABCGF* b_1' and b_2' lie along *MA* and *XY* respectively, and for the ring *CDEFG* b_1'' and b_2'' lie along *DY* and *ZM* respectively. Carbon atoms *B* and *E* must of necessity be situated in space above what in (VIII) would be the *ABDE* plane. The effect of this on the 6-membered ring *ABCDEF* is to permit staggering of adjacent C–H links at *D* and *E*—an advantage not associated with (VIII). Information concerning the C–C–C angles at *G* and *F* is not available: we assume them to be tetrahedral. From a model it is seen that *DY*, and *AM* and *XY* and *ZM* are roughly perpendicular to one another. We may therefore regard the carbon atoms *A*—*G* as comprising two 5-membered rings *ABCGF* and *CDEFG*, where b_1' is perpendicular to b_1'', so that, if in computing the molecular polarisability of the skeleton we, in effect, superimpose b_1'', b_2'', b_3'' appropriately on b_1', b_2', and b_3', we obtain a nearly isotropic whole. However, in so doing, we have used the *FG* and the *GC* link twice, and have not taken into consideration the bonds *F*–Me^3, *G*–Me^1, and *G*–Me^2. The contributions of *G*–Me^1 and *G*–Me^2 compensate for the double use of *FG* and *GC*, and accordingly, as a near estimate, it seems that it is only the anisotropy of polarisability of the C–C link *F*–Me^3 which could result in the camphor skeleton's becoming non-isotropic; in other words, we conclude that approximately $b_1^{sk} = b_2^{sk} = b_3^{sk}$, or $2b_1^{sk} \sim (b_2 + b_3)^{sk}$. This is in agreement with the values $2b_1^{sk} = 3{\cdot}14_6 \times 10^{-23}$ and $(b_2 + b_3)^{sk} = 3{\cdot}19_6 \times 10^{-23}$ obtained from our experimental $_\infty(_mK_2)$ for camphor.

Experimental

Materials.—The solutes were redistilled or recrystallised, as necessary, before use and had the b. p.s or m. p.s recorded for pure samples in Beilstein's "Handbuch." The authors thank Mr. D. G. Pettit for preparing *cyclo*hexane-1 : 4-dione. Solvents were purified as noted in ref. 6.

Infrared Spectrum of cyclo*Hexane*-1 : 4-*dione.*—This was kindly recorded, for a Nujol mull down to 650 cm.$^{-1}$ and for a solution ($w_2 = 0{\cdot}0533$) in benzene down to 1250 cm.$^{-1}$, by Mr. R. L. Werner (N.S.W. University of Technology). Absorption frequencies in cm.$^{-1}$ noted (other than those due to Nujol or benzene) were:

For the mull: 1710 (s and broad), 1404 (w), 1342 (w), 1325 (w), 1310 (m), 1295 (w), 1260 (vw), 1200 (vw), 1167 (w), 1142 (m), 1086 (w), 1062 (w), 964 (m), 925 (m), 872 (w), 803 (s);

For the solution: 1727 (s), 1417 (m), 1394 (w), 1330 (w shoulder), 1306 (m), 1290 (w, shoulder), 1258 (m).

(s = strong, m = medium, w = weak, v = very.)

The majority of these bands can be assigned straightforwardly to various C–H and skeletal motions. We follow Ramsay and Sutherland [39] in attributing the feature at 803 cm.$^{-1}$ to C–C stretching (802 cm.$^{-1}$ in the Raman spectrum of liquid *cyclo*hexane [39]). Absorptions at 1404 (mull) or 1417 cm.$^{-1}$ (solution) recall the observation by Francis [40] that CH_2 groups adjacent

Table 1. *Solvent constants.*

Temp.	10^7B_D	n_D	d_4^t	ϵ_1	H	J	$10^{14}{}_mK_1$
			Carbon tetrachloride				
20°	0·072	1·4604	1·5940	2·2360	2·064	0·4721	0·761
25	0·070	1·4575	1·5845	2·2270	2·060	0·4731	0·749
			Benzene				
25	0·410	1·4973	0·8738	2·2725	2·114	0·4681	7·56

to carbonyl display deformational frequencies *ca.* 1410 cm.$^{-1}$, *i.e.*, lower than the "normal" 1453 cm.$^{-1}$ found in, *e.g.*, *cyclo*hexane. For our purposes, however, the important point is that no sign was detected of OH absorption in the 3400—3600 cm.$^{-1}$ region. Apart from the C–H bands, the spectra of both Nujol and benzene were unaffected by the dione down to the point where $\nu_{C=O}$ became apparent.

[39] Ramsay and Sutherland, *Proc. Roy. Soc.*, 1947, *A*, 190, 245.
[40] Francis, *J. Chem. Phys.*, 1951, **19**, 942.

TABLE 2. *Weight fractions, Kerr constants, refractive indexes, and dielectric constants of solutions at 25°.*

10^5w_2	$10^7\Delta B$	n_D	d	ϵ
*cyclo*Hexane in carbon tetrachloride				
1574	−0·000$_5$	1·4567	1·55992	—
2618	—	1·4556	1·54280	—
3083	−0·001	—	1·53426	2·2188
3202	−0·001	1·4553	—	2·2185
4596	—	1·4546	—	2·2134
5343	−0·002	—	—	—
7036	−0·003	—	1·47413	2·1956
12,239	−0·005	—	—	—
whence $10^7\Delta B = -0{\cdot}0349w^2 - 0{\cdot}053w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = -0{\cdot}065_1$				
$\Sigma\Delta d/\Sigma w_2 = 1{\cdot}586_5$				
$\Sigma\Delta\epsilon/\Sigma w_2 = -0{\cdot}634_4$				
*cyclo*Hexyl bromide in carbon tetrachloride				
1646	0·168	—	—	—
2170	0·229	—	—	—
2189	0·249	1·4586	1·5782	2·3651
2567	0·274	1·4590	1·5770	2·3858
5241	0·582	1·4604	1·5692	2·5483
whence $10^7\Delta B = 10{\cdot}48w_2 + 12{\cdot}0w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = 0{\cdot}055$				
$\Sigma\Delta d/\Sigma w_2 = -0{\cdot}291_1$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 6{\cdot}18_4$				
*cyclo*Hexanone in carbon tetrachloride				
887	0·164	—	2·4018	1·5753
949	0·169	—	—	1·5751
1361	0·235	—	—	—
1771	0·322	—	—	1·5666
2159	0·382	1·4573	—	1·5622
2392	—	1·4572	2·6913	—
3128	0·563	1·4571	2·8319	1·5531
3734	—	1·4570	2·9491	—
whence $10^7\Delta B = 18{\cdot}0_7w_2 - 4{\cdot}0w_2^2$				
$\Sigma\Delta n/w_2 = -0{\cdot}012$				
$\Sigma\Delta d/\Sigma w_2 = -1{\cdot}014$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 19{\cdot}39$				
*cyclo*Pentyl chloride in carbon tetrachloride				
1516·5	0·083	1·4575	1·57122	2·3459
1781	0·097	—	1·56858	2·3708
1843	0·101	—	—	—
2730	0·150	1·4572	1·56054	2·4293
2753	0·151	1·4572	—	—
3550	0·195	1·4571	—	—
4901	0·270	1·4570	1·54183	2·6178
whence $10^7\Delta B = 5{\cdot}45w_2 + 1{\cdot}1w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = -0{\cdot}011$				
$\Sigma\Delta d/\Sigma w_2 = -0{\cdot}878_5$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 7{\cdot}831$				
*cyclo*Pentyl iodide in carbon tetrachloride				
1431	0·120	—	—	2·2949
1648	0·138	1·4595	1·58654	2·3012
2473	0·211	1·4597	1·58789	2·3383
2479	0·211	1·4598	—	—
2614	0·229	1·4603	—	—
3191	0·287	1·4604	—	—
6962	—	—	—	2·5431
7361	—	1·4638	1·59400	2·5588
whence $10^7\Delta B = 7{\cdot}64_1w_2 + 40{\cdot}6w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = 0{\cdot}093_6$				
$\Sigma\Delta d/\Sigma w_2 = 0{\cdot}1298$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 4{\cdot}53_5$				

10^5w_2	$10^7\Delta B$	n_D	d	ϵ
*cyclo*Hexyl chloride in carbon tetrachloride				
584	0·043	—	—	—
771	0·068	—	—	—
1657	0·166	—	1·5696	2·3565
2388	0·216	—	—	—
3167	0·302	1·4576	1·5562	2·4738
4984	0·479	1·4578	1·5431	2·6151
9586	0·873	—	—	—
whence $10^7\Sigma B = 9{\cdot}71w_2 - 6{\cdot}1w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = 0{\cdot}0049$				
$\Sigma\Delta d/\Sigma w_2 = -0{\cdot}862_6$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 7{\cdot}79_4$				
*cyclo*Hexyl iodide in carbon tetrachloride				
906	0·100	1·4585	1·58467	2·2710
928	0·102	1·4587	—	—
1054	0·117	1·4588	—	—
1590	0·174	1·4594	—	—
1923	0·212	1·4596	1·58478	2·3183
1445	0·266	1·4601	1·58486	2·3440
whence $10^7\Delta B = 11{\cdot}17w_2 - 10{\cdot}96w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = 0{\cdot}114_8$				
$\Sigma\Delta d/\Sigma w_2 = 0{\cdot}0131$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 4{\cdot}78_4$				
*cyclo*Pentane in carbon tetrachloride				
5678	−0·004	1·4503	1·48664	2·1948
7155	−0·005	—	—	—
9289	−0·006	—	—	—
11,697	−0·007	1·4426	1·39543	2·1641
12,889	−0·007	—	—	—
18,979	−0·009	1·4334	1·30270	2·1327
whence $10^7\Delta B = -0{\cdot}077w_2 + 0{\cdot}16w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = -0{\cdot}127$				
$\Delta d = -1{\cdot}827w_2 + 1{\cdot}8w_2^2$				
$\Delta\epsilon = 0{\cdot}600w_2 + 0{\cdot}54w_2^2$				
*cyclo*Pentyl bromide in carbon tetrachloride				
658	0·051	—	—	—
911	0·063	1·4578	1·5825	2·2819
2191	0·139	—	—	—
2231	0·155	1·4581	1·5797	2·3617
3080	0·218	1·4588	1·5780	2·4155
4592	0·345	—	—	—
whence $10^7\Delta B = 6{\cdot}19_5w_2 + 28{\cdot}2w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = 0{\cdot}035$				
$\Sigma\Delta d/\Sigma w_2 = -0{\cdot}2137$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 6{\cdot}07_7$				
*cyclo*Pentanone in carbon tetrachloride				
403	0·075	—	—	—
477	0·080	—	—	—
533	0·091	—	—	—
559	0·099	—	1·5789$_5$	2·3473
607	0·105	—	—	—
768	0·134	—	—	—
889	0·156	—	—	—
1073	0·190	1·4572	1·5738$_5$	2·4508
1118	0·198	—	1·5734	2·4566
1228	0·218	—	—	—
1336	0·238	—	—	—
1886	—	1·4571	1·5658	2·6204
3219	—	1·4569	—	—
whence $10^7\Delta B = 16{\cdot}9_8w_2 + 64w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = -0{\cdot}021$				
$\Sigma\Delta d/\Sigma w_2 = -0{\cdot}992_2$				
$\Sigma\Delta\epsilon/\Sigma w_2 = 20{\cdot}86$				

TABLE 2. (*Continued.*)

10^6w_2	$10^7\Delta B$	n_D	d	ε
Tetrahydrofuran in carbon tetrachloride				
1336	−0·002	1·4571	1·56878	2·3406
2943	−0·005	—	—	—
4443	—	1·4565	1·53316	2·6048
5118	$-0·007_5$	—	—	—
5656	−0·008	1·4545	1·51930	2·7067
6235	$-0·009_5$	—	—	—
10,103	−0·015	—	—	—
whence $10^7\Delta B = -0·152_1w_2 + 0·42_4w_2^2$				
$\Sigma\Delta n/\Sigma w_2 = -0·038_5$				
$\Sigma\Delta d/\Sigma w_2 = -1·158$				
$\Sigma\Delta\varepsilon/\Sigma w_2 = 8·49_2$				

10^6w_2	$10^7\Delta B$	n_D	d	ε
(±)-*Camphor in carbon tetrachloride*				
482	0·034	—	—	—
1086	0·081	1·4580	—	—
1134	0·091	1·4581	—	—
1432	—	1·4582	1·5702	2·4020
2274	0·186	1·4585	1·5624	2·5044
2945	0·245	1·4588	1·5562	2·5863
4769	—	1·4597	1·5390	2·7987
whence $10^7\Delta B = 7·36w_2 + 33w_2^2$				

*cyclo*Hexane-1 : 4-dione in benzene

10^6w_2	418	649	924	1123	1315	2048	3227	3849
$10^7\Delta B$	−0·010	−0·013	−0·013	−0·018	−0·034	−0·038	−0·067	−0·072

whence $10^7\Delta B = -2·01_4w_2 + 2·1w_2^2$

Paraldehyde in carbon tetrachloride at 20°

10^6w_2	1918	2902	4400	5004	9488	9654	10,833	14,561
$10^7\Delta B$	−0·097	−0·090	−0·170	−0·205	−0·494	−0·473	−0·574	−0·757

whence $\Delta B = -3·99w_2 - 9·4w_2^2$

TABLE 3. *Calculation of molar Kerr constants at infinite dilution at 25°.*

Solute	$\alpha\varepsilon_1$	β	γ	δ	$10^{12}{}_\infty(_mK_2)$
*cyclo*Hexane	$-0·034_4$	−1·001	−0·045	−0·499	$0·98_7$
*cyclo*Hexyl chloride	$7·79_4$	−0·544	0·003	138·7	121·3
,, bromide	$6·18_4$	−0·184	0·038	149·7	180·7
,, iodide	$4·78_4$	$0·008_2$	0·078	159·5	248·8
*cyclo*Hexanone	19·39	−0·640	−0·008	258·1	184·2
*cyclo*Hexane-1 : 4-dione *	1·45₇ †	0·239 †	−0·010 †	$-4·91_2$	$-41·2_2$
*cyclo*Pentane	−0·600	$-1·15_5$	−0·087	−1·10	$0·75_1$
*cyclo*Pentyl chloride	$7·83_1$	−0·554	−0·007	77·86	$59·3_1$
,, bromide	$6·07_7$	−0·135	0·024	$88·50_9$	$96·8_3$
,, iodide	$4·53_5$	$0·081_9$	0·064	109·2	158·4
*cyclo*Pentanone	$20·8_6$	−0·626	−0·014	242·6	147·6
Tetrahydrofuran	$8·49_2$	−0·731	−0·026	$-2·17_4$	$-2·39_2$
Paraldehyde	6·21 ‡	−0·605 ‡	−0·062 ‡	$-55·4_2$ ¶	$-57·0_2$
(±)-Camphor	$12·1_8$	−0·612	0·032	105·1	$115·0_5$

* Solvent : benzene; in other cases, carbon tetrachloride.
† Recalc. from Le Fèvre and Le Fèvre.[26] ‡ From Le Fèvre, Mulley, and Smythe.[24]
¶ Measured at 20°.

TABLE 4. *Values of* $\theta_1 + \theta_2$ *and* $b_{\text{TOT.}}$

	$10^{35}(\theta_1 + \theta_2)$	R_∞ (c.c.)	$10^{23}(b_1 + b_2 + b_3)$	Source from which R_∞ is calculated
*cyclo*Hexane	$0·23_5$	27·15	3·209	12*a*
*cyclo*Hexyl chloride	28·85	32·26	3·813	12*b*
,, bromide	42·97	34·71	4·103	12*b*
,, iodide	59·17	39·70	4·692	12*b*
*cyclo*Hexanone	43·80	27·25	3·221	12*a*
*cyclo*Hexane-1 : 4-dione	−9·80	27·31	3·228	*x*
*cyclo*Pentane	0·179	22·57	2·667	12*a*
*cyclo*Pentyl chloride	14·10	27·33	3·230	12*b*
,, bromide	$23·02_5$	30·21	3·571	12*b*
,, iodide	37·66	35·15	4·155	12*b*
*cyclo*Pentanone	35·11	22·79	2·694	12*a*
Tetrahydrofuran	−0·569	19·38	2·291	*y*
Paraldehyde	−13·56	31·70	3·746	*z*
(±)-Camphor	27·36	44·01 *	5·201	*z*

* *I.e.*, R_D calc. from bond refractions. Refs. : *x*, Clarke, *J.*, 1912, **101**, 1788. *y*, Böhme and Schurhoff, *Chem. Ber.*, 1951, **84**, 41. *z*, Vogel, Cresswell, Jeffery, and Leicester, *J.*, 1952, 514.

TABLE 5. *Polarisations at 25° and estimations of dipole moment.*

Solute	$_{\infty}P_2$ (c.c.)	R_D (c.c.)	μ (D) *
*cyclo*Hexane	27·8	27·7	0
*cyclo*Hexyl chloride	131·5	33·0	2·18
,, bromide	142·2	35·6	$2\cdot2_6$
,, iodide	144·7	$41\cdot0_5$	$2\cdot2_3$
*cyclo*Hexanone	231·1	27·87	3·14
*cyclo*Hexane-1 : 4-dione †	59·8 ‡	27·7	$1\cdot2_3$
*cyclo*Pentane	23·2	23·1	0
*cyclo*Pentyl chloride	116·6	27·96	$2\cdot0_4$
,, bromide	126·9	30·99	$2\cdot1_5$
,, iodide	127·2	36·38	$2\cdot0_9$
*cyclo*Pentanone	211·0	23·31	$3\cdot0_2$
Tetrahydrofuran	87·8	19·87	$1\cdot8_1$
(±)-Camphor	241·4	44·0	$3\cdot0_9$

* Calc. by assuming $_DP = 1\cdot05R_D$. † Solvent: benzene. In other cases, carbon tetrachloride.
‡ Recalc. from ref. 38.

TABLE 6. *Previously recorded dipole moments.*

*cyclo*Hexane	B. 25°. 28 c.c. 0 (1)
*cyclo*Hexyl chloride	B. 25°. 143 c.c. 2·3 (1)
	B. 60°. $_0P = 91$ c.c. 2·07 (2)
	B. 18°. $_0P = 94$ c.c. 2·10 (3)
*cyclo*Hexyl bromide	B. 25°. 150 c.c. 2·3 (1)
	B. 60°. $_0P = 95$ c.c. 2·11 (2)
,, iodide	B. 60°. $_0P = 83$ c.c. 1·98 (2)
*cyclo*Hexanone	B. No exptl. details. 2·75 (4)
	B. 25°. 202 c.c. 2·9 (1)
	B. 25°. 211·8 c.c. 3·01 (5)
	D. 25°. 202·2 c.c. 2·90 (6)
	B. 19°. Dielectric loss method. 3·02 (7)
	B. 18·5°. ,, ,, 2·90 (8)
	B. 20°. 225·4 c.c. 3·08 (9)
	CH. 20°. 219·7 c.c. 3·04 (9)
	CT. 20°. 232·8 c.c. 3·14 (9)
*cyclo*Pentane	liq. 20°. $\varepsilon = 1\cdot965$. $n_D^2 = 1\cdot984$. 0 (10)
*cyclo*Pentyl chloride	B. 25°. 117·2 c.c. 2·08 (11)
,, bromide	B. 25°. 130·0 c.c. 2·20 (11)
,, iodide	B. 25°. 122·8 c.c. 2·06 (11)
*cyclo*Pentanone	B. 22°. $_0P = 192 \pm 4$ c.c. 3·00 ± 0·03 (12)
	B. 25°. 197·0 c.c. 2·93 (5)
	B. 20°. 196·3 c.c. 2·86 (9)
	CH. 20°. 187·2 c.c. 2·81 (9)
	CT. 20°. 201·3 c.c. 2·93 (9)
Tetrahydrofuran	B. 25°. $_0P = 60\cdot9$ c.c. 1·71 (13)
	D. 25°. $_0P = 67\cdot8$ c.c. 1·81 (13)
	B. 20°. No pol^{ns}. given. 1·68 (14)
Camphor	B. 22°. $_0P = 190 \pm 4$ c.c. 2·95 ± 0·03 (12)
	B. 22°. $_0P = 181 \pm 3$ c.c. 2·94 ± 0·03 (15)
	B. 20°. 242 c.c. 3·05 (16)
	Hp. Temp. variation of dielectric absn. 2·98 (7)
	Hp. Wave-length variation of dielectric absn. 2·97 7)
	B. 20°. *ca.* 235 c.c. 2·90—2·91 (17)
	B. 25°. 241·4 c.c. 3·10 (18)

[1] Williams, *J. Amer. Chem. Soc.*, 1930, **52**, 1831. [2] Hassel and Naeshagen, *Z. physikal. Chem.*, 1932, **15**, *B*, 373. [3] *Idem*, *ibid.*, 1936, **19**, *B*, 434. [4] Wolf, *ibid.*, 1929, **3**, *B*, 128. [5] Bentley, Everard, Marsden, and Sutton, *J.*, 1949, 2957. [6] Halverstadt and Kumler, *J. Amer. Chem. Soc.*, 1942, **64**, 1982. [7] Whiffen and Thompson, *Trans. Faraday Soc.*, 1946, **52**, *A*, 114, 122. [8] Cripwell and Sutherland, *ibid.*, p. 149. [9] Gunthard and Gäumann, *Helv. Chim. Acta*, 1951, **34**, 39. [10] Arkel, Meerlung, and Handel, *Rec. Trav. chim.*, 1942, **61**, 767. [11] Rogers and Roberts, *J. Amer. Chem. Soc.*, 1946, **68**, 843. [12] Donle and Volkert, *Z. physikal. Chem.*, 1930, **8**, *B*, 60. [13] Smyth and Walls, *J. Amer. Chem. Soc.*, 1932, **54**, 3230. [14] Robles, *Rec. Trav. chim.*, 1939, **58**, 111. [15] Wolf, *Phys. Z.*, 1930, **31**, 227. [16] Higasi, *Bull. Inst. Phys. Chem. Res. Tokyo*, 1932, **11**, 729. [17] Sahney, Barucha, and Sarna, *J. Ind. Chem. Soc.*, 1948, **25**, 285. [18] Le Fèvre and Maramba, *J.*, 1952, 235.

Measurements.—These were made by the methods described earlier,[7] when the symbols used here were defined and the extrapolation procedure was explained. The observations recorded in Table 2 are for 20° or 25°, at which the appropriate data for the two solvents involved are listed in Table 1. The calculations of $_{\infty}(_mK_2)$ are in Table 3. Other necessary quantities follow as Table 4.

Polarisations and Dipole Moments.—Incidental to determination of ${}_{\infty}(_{m}K_{2})$ is the provision of data from which ${}_{\infty}P_{2}$ may be calculated; by using the approximation that ${}_{D}P = 1{\cdot}05R_{D}$, apparent moments for the solutes now under examination have been calculated (see Table 5).

It is seen that the moments of the bromides exceed those of the chlorides. Such is not always the case: μ_{CH_3Cl} is greater [41] than μ_{CH_3Br}, and the same is true of ethyl chloride and bromide.[42] However, with increase in size of the alkyl radical the relation is reversed, the polarities of *n*-propyl and *n*-butyl chloride being less than those of the corresponding bromides.[41]

Except with *cyclo*-pentanone and -hexanone, carbon tetrachloride has not hitherto been used as solvent. Recorded determinations, mostly in benzene, display some variability among themselves, but, even so, change of medium does not appear to cause marked effects. Comparison with previous measurements is best made *via* figures for ${}_{\infty}P_{2}$ (when these are accessible) since the μ's quoted by other workers depend on the particular convention adopted to estimate distortion polarisations. Table 6 briefly summarises the literature. The code of the M.I.T Tables [43] is used to indicate solvent and temperature (B = benzene, CH = *cyclo*-hexane, CT = carbon tetrachloride, D = dioxan, Hp = heptane). Polarisations (total in most cases, orientation ${}_{O}P$ in some) are shown as c.c.; they are followed by the moment actually given in the reference cited in parentheses.

The authors gratefully acknowledge financial assistance from Imperial Chemical Industries, Australia and New Zealand, Ltd., and a gift of *cyclo*pentane from Caltex Oil (Australia) Pty. Ltd.

UNIVERSITY OF SYDNEY, N.S.W., AUSTRALIA. [*Received, February 20th*, 1956]

[41] Buckingham and Le Fèvre, *J.*, 1953, 3432.
[42] Sugden and Groves, *J.*, 1937, 158.
[43] Wesson, "Tables of Electric Dipole Moments," Technology Press, Massachusetts Inst. Technology, 1948.

---

687. *Studies in Pyrolysis. Part VII.* Model Systems for the Pyrolysis of Poly(ethylene Terephthalate): 2 : 2′-Dibenzoyloxydiethyl Ether, 2-Benzoyloxyethyl Vinyl Ether, and Certain Related Vinyl Ethers.*

By H. V. R. IENGAR and P. D. RITCHIE.

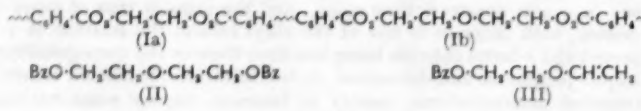
In a vapour-phase flow-reaction vessel (*ca.* 450—500°), 2 : 2′-dibenzoyloxydiethyl ether yields a complex pyrolysate best explained by the following reaction sequence. Stage 1: Alkyl–oxygen scission at an ester group, yielding 2-benzoyloxyethyl vinyl ether and benzoic acid. Stage 2: Secondary breakdown of 2-benzoyloxyethyl vinyl ether by three competitive routes, (i) alkyl–oxygen scission at the ether group, yielding vinyl benzoate and acetaldehyde, (ii) disproportionation to ethylene dibenzoate and 1 : 2-divinyloxyethane, and (iii) alkyl–oxygen scission at the ester group, yielding benzoic acid and vinyl ether. Stage 3: A series of tertiary breakdowns of the primary and secondary products. These conclusions are supported by the pyrolysis of divinyl, *n*-butyl vinyl, and *iso*butyl vinyl ethers. The bearing of the results on the pyrolysis of technical poly(ethylene terephthalate) is discussed.

ETHYLENE DIBENZOATE and vinyl benzoate have been used in previous studies [1,2] on the pyrolysis of poly(ethylene terephthalate), as model systems to represent the behaviour of a typical segment (Ia) in the polyester chain. Since it is known that occasional ether linkages (*e.g.*, diethylene glycol units) are unavoidably incorporated into the chain during polycondensation, the work has now been extended to an analogous pair of models, 2 : 2′-dibenzoyloxydiethyl ether (II) and 2-benzoyloxyethyl vinyl ether (III), to represent the behaviour of a chain segment (Ib).

The ether-diester (II), which is stable up to *ca.* 350° in a vapour-phase flow-reaction

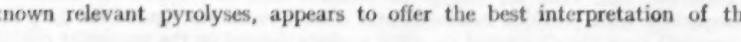
* Part VI, *J.*, 1956, 2628.
[1] Allan and Ritchie, *Chem. and Ind.*, 1953, 747.
[2] Allan, Forman, and Ritchie, *J.*, 1955, 2717.

vessel breaks down at *ca.* 450—500° to an extremely complex pyrolysate containing some fourteen constituents. It is possible to formulate more than one reaction scheme to account for these; but the following sequence, based on a correlation of the present results

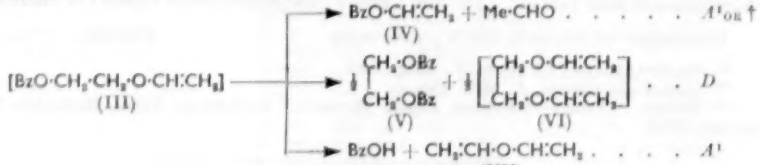


with other known relevant pyrolyses, appears to offer the best interpretation of the breakdown.

Stage 1 : Alkyl–oxygen scission at one of the two (identical) ester groupings, thus :

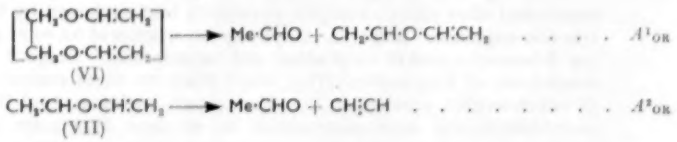


Stage 2 : Secondary breakdown of the relatively unstable ether-ester (III) by three competitive routes :



† For meaning of symbols, see Discussion.

Stage 3 : A series of tertiary breakdowns (i) of vinyl benzoate (IV), by the three competitive routes (A^2, C^2, R/C^1) noted by Allan, Forman, and Ritchie,[2] (ii) of ethylene dibenzoate (V), by the A^1 and D routes,[2] (iii) of acetaldehyde, by decarbonylation, (iv) of benzoic acid, by decarboxylation, and (v) of the unstable diether (VI), by the following consecutive routes :



The postulated relatively unstable intermediates (III) and (VI) were not identified directly; but (III) and the ether (VII) have been pyrolysed separately, with results in accord with the overall three-stage scheme. All the other products required by the scheme were identified, either chemically or by infrared spectrometry—carbon monoxide and dioxide, acetaldehyde, methane, benzoic acid and anhydride, benzene, vinyl benzoate, styrene, acetophenone, ethylene dibenzoate, vinyl ether, and acetylene (together with ethylene, the origin of which is not certain).

It is certain that free-radical mechanisms operate in at least some of the stages of this complex sequence of high-temperature reactions. The fact that the changes are formulated here, for simplicity, as molecular reactions is not intended to imply the absence of radical mechanisms; indeed, it is difficult to account for the formation of ethylene on any other basis.

Discussion

To interpret more clearly the pyrolysis of the ether-esters studied, it is first necessary to survey briefly the pyrolysis of ethers in general.

Saturated Aliphatic Ethers.—A simple ether breaks down by a primary alkyl–oxygen scission : [3]

$$\text{>CH·O·CH<} \longrightarrow \text{>CO} + \text{CH}_2\text{<} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad A^1_R$$

The suffix R indicates that hydrogen is transferred across the point of scission to the hydrocarbon group R of an ether R–O–R. Transfer in the opposite sense, to the alkoxyl grouping OR (A^1_{OR} scission), is not observed.

Alkyl Vinyl Ethers.—In addition to the type of rearrangement discussed later, two initial types of scission are here formally possible, *viz.*, alkyl–oxygen (A^1) and alkenyl–oxygen (A^2), each with two possible alternative variations, thus :

$$\text{CH}_2\text{:CH·O·CH}_2\text{·CH}_2\text{R} \longrightarrow [\text{CH}_2\text{:CH·OH}] + \text{CH}_2\text{:CHR} \quad . \quad . \quad . \quad . \quad . \quad A^1_{OR}$$

$$\textit{or} \qquad \longrightarrow \text{CH}_2\text{:CO} + \text{CH}_3\text{·CH}_2\text{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad A^1_R$$

$$\textit{or} \qquad \longrightarrow \text{CH}\vdots\text{CH} + \text{CH}_2\text{R·CH}_2\text{·OH} \quad . \quad . \quad . \quad . \quad . \quad A^2_{OR}$$

$$\textit{or} \qquad \longrightarrow \text{CH}_2\text{:CH}_2 + \text{CH}_2\text{R·CHO} \quad . \quad . \quad . \quad . \quad . \quad A^2_R$$

Wang and Winkler [4] found that ethyl vinyl ether yields acetaldehyde and ethylene (first-order reaction : *ca.* 380—450°) ; but here, since R = H, the evidence does not discriminate between routes A^1_{OR} and A^2_R, both of which would yield the same pair of primary products. It is now shown that A^1_{OR} is the favoured route for alkyl vinyl ethers, since the two butyl vinyl ethers (VIII) and (IX) both yield acetaldehyde and a butene smoothly at *ca.* 500°, with no evidence for formation of a butyraldehyde and ethylene by route A^2_R; neither is there evidence for routes A^1_R or A^2_{OR}.

$$\underset{\text{(VIII)}}{\text{CH}_2\text{:CH·O·CH}_2\text{·CH}_2\text{Et}} \longrightarrow \text{Me·CHO} + \text{CH}_2\text{:CHEt} \quad . \quad . \quad . \quad . \quad . \quad A^1_{OR}$$

$$\underset{\text{(IX)}}{\text{CH}_2\text{:CH·O·CH}_2\text{·CHMe}_2} \longrightarrow \text{Me·CHO} + \text{CH}_2\text{:CMe}_2 \quad . \quad . \quad . \quad . \quad . \quad A^1_{OR}$$

On the other hand, Hasche and Thompson [5] have reported that alkyl vinyl ethers ($\text{CH}_2\text{:CH·O·R}$), over a wide range of temperatures and pressures, rearrange to isomeric aldehydes ($\text{R·CH}_2\text{·CHO}$). Pyrolysis of the butyl vinyl ethers (VIII) and (IX) produced neither C_6-aldehydes nor the pentanes which these should yield on decarbonylation; nevertheless, some ethers exhibiting 1 : 2-unsaturation, such as allyl vinyl ether, certainly rearrange thermally in this way.[6,7]

Vinyl ether (VII), being fully symmetrical and unsaturated, presents a special case. Taylor [8] concluded that this ether breaks down (sealed tube : *ca.* 450°) by a complex series of free-radical reactions, and that the major scission-route is :

$$\text{(VII)} \quad \text{CH}_2\text{:CH·O·CH:CH}_2 \longrightarrow \text{CH}_2\text{:CO} + \text{CH}_3\text{·CH}_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad A^1_R$$

However, in the flow vessel now employed (*ca.* 500°), breakdown occurs by the following A^2_{OR} route, with no evidence for rearrangement :

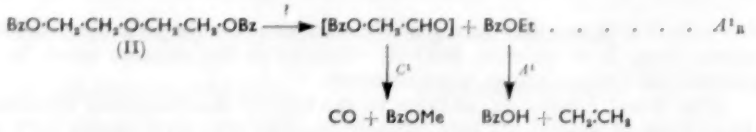
$$\text{(VII)} \quad \text{CH}_2\text{:CH·O·CH:CH}_2 \longrightarrow \text{Me·CHO} + \text{CH}\vdots\text{CH} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad A^2_{OR}$$

In the light of these considerations, the present pyrolyses can now be more critically interpreted.

Competitive Ether- and Ester-scissions.—The primary breakdown of ether-diester (II) by alkyl–oxygen scission at an ester grouping, rather than at the ether grouping (Stage 1), is supported by a number of analogies. For example, ethyl carboxylates in general show A^1 scission well below 500°, whereas ethyl ether is stable [3] at *ca.* 500° though it undergoes A^1_R scission at *ca.* 550°. This thermal selectivity is confirmed by the complete absence

[3] Hurd, "The Pyrolysis of Carbon Compounds," Chemical Catalog Co., New York, 1929, Chap. 8.
[4] Wang and Winkler, *Canad. J. Res.*, 1943, **21**, *B*, 97.
[5] Hasche and Thompson, U.S.P. 2,294,402/1942.
[6] Claisen, *Ber.*, 1896, **29**, 2932.
[7] Hurd and Pollack, *J. Amer. Chem. Soc.*, 1938, **60**, 1905.
[8] Taylor, *J. Chem. Phys.*, 1936, **4**, 116.

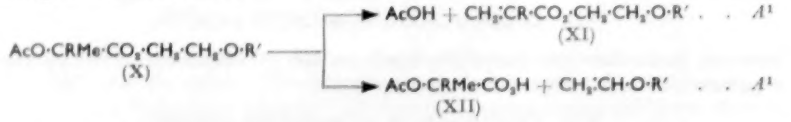
of methyl benzoate from the pyrolysate from (II); for, if the ether grouping provided a point of scission, it should be possible to detect end-products from the following predictable sequence :



Ethyl benzoate should be largely destroyed at *ca.* 500°, and ethylene is, in fact, obtained on pyrolysis of both (II) and (III); but, since vinyl benzoate (IV) is also formed in each case, and since it is known [9] that on pyrolysis this vinyl ester yields ethylene (*inter alia*) by some unknown route, formation of the olefin cannot here be taken, by itself, as evidence for ethyl benzoate as its precursor. However, methyl benzoate is a very thermostable ester; [9] its complete absence therefore indicates A^1 scission of (II) at an ester grouping as the sole primary breakdown route at *ca.* 450—500°.

This same evidence indicates that the ether-ester (III) does not break down by A^2_R scission to ethylene and the unstable benzoyloxyacetaldehyde. This agrees with the known pyrolysis of alkyl vinyl ethers such as (VIII) and (IX); but it would be expected that pyrolysis of (III) should occur by the A^1_{OR} scission characteristic of such ethers, in competition with A^1 scission of the ester grouping, and the overall breakdown of (III) is best interpreted as a competition between A^1_{OR}, *D*, and A^1 routes (Stage 2). The disproportionation route is proved by the occurrence of ethylene dibenzoate (V) (see below), though the evidence for the two alkyl–oxygen scissions (A^1_{OR} and A^1) is less direct. Mere identification of vinyl benzoate and acetaldehyde in the pyrolysate from (III) does not of itself prove an A^1_{OR} scission or identification of benzoic acid and vinyl ether an A^1 scission, since these four products could also arise by further breakdown (Stage 3) of the products from the *D* route. However, the A^1_{OR} route is strongly supported by the known breakdown of alkyl vinyl ethers, and the A^1 route by the fact that vinyl ether (VII) was identified in one run at *ca.* 470° in which no ethylene dibenzoate was detected. This slight variation between the results of two similar runs may be due to different degrees of carbonisation at the wall of the reactor, or to unintentional variations in feed rate or temperature.

The conclusion that primary breakdown of the ether-diester (II) occurs by an A^1 scission agrees well with the known pyrolysis (*ca.* 450—500°) of certain ether-diesters (X) in which the presence of two dissimilar ester groupings offers the formal possibility of two competing A^1 scissions, thus :

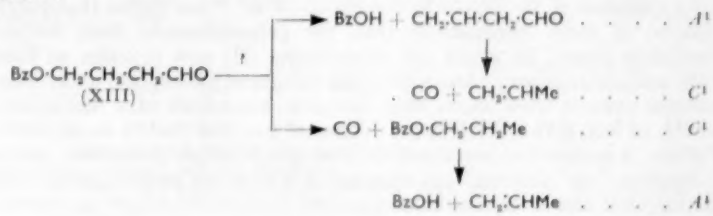


Burns, Jones, and Ritchie [10] found that the esters (X; R = Me, R′ = Me or Ph) follow the first of these routes, giving α-methylacrylates (XI; R = Me) in yields up to at least 76%. Similarly, Fein, Ratchford, and Fisher [11] found that the esters (X; R = H, R′ = Me, Et, Bu^n, or tetrahydrofurfuryl) produce acrylates (XI; R = H) by the first route; but here the yield is generally low. This poor yield may be due to secondary breakdown of the primary products; alternatively, or in addition, there may be competitive primary scissions—either an A^1_R breakdown of the original ether grouping (–CH_2·CH_2·O·R′), or formation of the acid (XII) and an alkyl vinyl ether by way of the second A^1 route. No such ethers were, in fact, observed; but their known breakdown-product, acetaldehyde, was noted by Fein *et al.*[11] in the pyrolysates from the methoxy- and ethoxy-esters.

[9] Engler and Low, *Ber.*, 1893, **26**, 1440.
[10] Burns, Jones, and Ritchie, *J.*, 1935, 714.
[11] Fein, Ratchford, and Fisher, *J. Amer. Chem. Soc.*, 1944, **66**, 1201.

Another probable source of this aldehyde is the known thermal breakdown [12] of α-acetoxypropionic acid (XII; R = H). There is, therefore, direct evidence for the first A^1 scission, and indirect evidence for competition by the second: there is no positive evidence for primary scission at the original ether grouping, though the unspecified gaseous hydrocarbons reported by Fein *et al.*[11] may have included products indicative of a minor scission at this point.

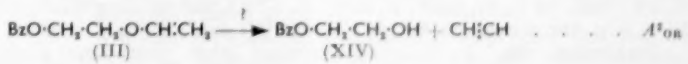
Rearrangement of Vinyl Ethers.—The vinyl ethers (VII), (VIII), and (IX) show no pyrolytic rearrangement; and the pyrolysis of ether-ester (III) is consistent with this, there being evidence of competitive scissions (A^1 and $A^1{}_{OR}$) and disproportionation (D) only. If rearrangement (R) to γ-benzoyloxybutyraldehyde (XIII) also competed to any measurable extent, it should be possible to detect end-products from the following predictable sequence:



There was, however, no sign of propene or its immediate precursors, though all were carefully sought by infrared spectrometry.

Disproportionation.—Ethylene dibenzoate (V) is present in the pyrolysates from the ether-diester (II: *ca.* 450°) and from the ether-ester (III: *ca.* 470°), though at higher temperatures it is destroyed, as might be predicted from earlier results.[2] Its formation can be readily explained only by assuming a disproportionation of the ether-ester (III), the accompanying product being the diether (VI). The latter substance was not identified, probably owing to the relatively easy pyrolysis of vinyl ethers in general; but its predictable scission-products, acetaldehyde and vinyl ether (VII), were identified. The latter survived the temperature of the reaction vessel in small amount only, and was detected by infrared spectrometry, though its known secondary scission-products, acetaldehyde and acetylene, were readily observed. In view of Taylor's results,[8] keten was carefully sought, since it is a formally possible breakdown-product of the vinyl ethers (III) and (VI) by $A^1{}_R$ and of (VII) by $A^2{}_R$ scission; but no evidence for this product could be found.

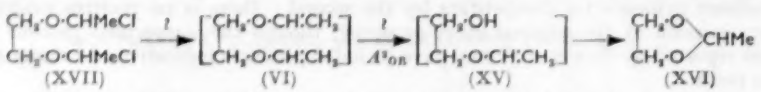
Origin of Acetylene.—This substance is attributed to two sources—the observed $A^2{}_{OR}$ scission of vinyl ether (VII), and the already known alkenyl–oxygen scission (A^2) of vinyl benzoate (IV).[2] Two other formally possible sources can be eliminated—$A^2{}_{OR}$ scission of the vinyl ethers (III) and (VI). If the former breaks down in this way, the accompanying primary product should be 2-hydroxyethyl benzoate (XIV), thus:



However, the hydroxy-ester (XIV) yields water (*inter alia*) on pyrolysis;[13] and water was not observed in any of the present pyrolysates, though carefully sought. If, on the other hand, acetylene arose by $A^2{}_{OR}$ scission of the diether (VI), the accompanying primary product should be 2-hydroxyethyl vinyl ether (XV), a substance which is very readily cyclised to the acetal (XVI).[14] Hurd and Botterton,[15] in an attempt to prepare the

[12] Bagard, *Bull. Soc. chim. France*, 1907, **1**, 307.
[13] Cretcher and Pittenger, *J. Amer. Chem. Soc.*, 1925, **47**, 2560.
[14] Hill and Pidgeon, *ibid.*, 1928, **50**, 2718.
[15] Hurd and Botterton, *ibid.*, 1946, **68**, 1200.

diether (VI) by dehydrochlorinating the chlorinated diether (XVII), unexpectedly obtained the cyclic acetal instead; and this suggests the following possible sequence of reactions :



It appears, however, that another explanation must be sought for Hurd and Botterton's result, since a repetition of their experiment has shown no liberation of acetylene. This fact, coupled with the failure of the butyl vinyl ethers (VIII) and (IX) to yield acetylene on pyrolysis, strongly argues against A^2_{OR} scissions of either (III) or (VI) as a source of the observed acetylene.

Application of the Results to Polyesters.—Pohl [16] has shown that poly(ethylene terephthalate) is more thermostable than the polycondensate from terephthalic acid and diethylene glycol, for which the ether-diester (II) now provides an ideal model system. Pohl used, as an index of breakdown, the volume of gas evolved under standard conditions; and the present work shows that complete breakdown of a diethylene glycol unit (Ib) would, in fact, give a much larger volume of gas than that of an ethylene glycol unit (Ia). Further, it is clear that acetaldehyde, a recognised major breakdown-product of commercial " Terylene " or " Dacron," can arise not only from the predominating chain-segments such as (Ia),[2] but also from occasional segments such as (Ib) which are unavoidably present to some extent in the polyester chain.

Pohl worked with molten polyesters, whereas the present studies cover vapour-phase pyrolyses. Caution is clearly required in correlating the results; but experiments which will be described in a future communication show that the correlation is permissible for this groups of compounds.

Experimental

Apparatus.—Pyrex-glass flow-reaction vessels of the type previously described [2] were used, with the same system for collecting pyrolysate fractions, and with temperatures automatically controlled to within ±5°. Before each run the whole system was flushed with nitrogen, to avoid oxidation of the heated vapour.

Analytical Methods.—Aldehydes and ketones were characterised as their 2 : 4-dinitrophenylhydrazones (mixed m. p. or, where specified, paper chromatography [17]). All other solid products were identified by mixed m. p. Keten was sought in gaseous pyrolysates by means of the usual aniline trap. The normal chemical examination of pyrolysate fractions was in many cases supplemented by infrared spectrometry.

The Table summarises the experimental conditions for 9 runs. It shows the amount (*a*) of liquid pyrolysate (excluding minor amounts of volatile materials condensed in the cold trap, cooled in solid carbon dioxide) and also the amount (*b*) and composition of the final exit-gases. All gas analyses are reported on a nitrogen-free basis.

2 : 2′-*Dibenzoyloxydiethyl Ether* (II).—*Preparation* (*A*). Dry sodium benzoate (50 g.), 2 : 2′-dichlorodiethyl ether (100 g.), and a few drops of diethylamine, heated at 200° for 6 hr., yielded 2-benzoyloxyethyl 2-chloroethyl ether, b. p. 166°/8 mm. (lit.,[18] 191°/25 mm.) (Found : C, 58·1; H, 6·0. Calc. for $C_{11}H_{13}O_3Cl$: C, 57·8; H, 5·7%), and the ether-diester (II) (10 g., 18%), m. p. 33·5°, b. p. 250°/3 mm. (lit.,[18] b. p. 279—281°/24 mm.; no m. p. recorded previously).

Preparation (*B*). 2 : 2′-Dihydroxydiethyl ether (diethylene glycol), on benzoylation (Schotten–Baumann), yielded the ether-diester (II) (47%) (Found : C, 68·6; H, 6·0. Calc. for $C_{18}H_{18}O_5$: C, 68·8; H, 5·7%).

Pyrolysis 1. Distillation of (*a*) yielded acetaldehyde, followed by (i) 6 g., b. p. 80—90° (mainly benzene, characterised as *m*-dinitrobenzene), (ii) 2·6 g., b. p. 90—120°, and (iii) 1·6 g., b. p. 120—160° (containing styrene; infrared). Benzoic acid was removed from the residue, by sodium hydrogen carbonate; further distillation then yielded (iv) 1·4 g., b. p. 160—210° (containing acetophenone), (v) 4 g., b. p. 210—280°, and (vi) 8·5 g., high-boiling residue. The gaseous pyrolysate (*b*) contained carbon monoxide and dioxide, methane, ethylene, and

[16] Pohl, *J. Amer. Chem Soc.*, 1951, **73**, 5660.
[17] Burton, *Chem. and Ind.*, 1954, 576.
[18] Cretcher, Koch, and Pittenger, *J. Amer. Chem. Soc.*, 1925, **47**, 1175.

acetylene, but no propene (infrared). As in previous related pyrolyses,[3] the infrared spectrum of (*b*) showed a strong unallocated band at 1140 cm.$^{-1}$. Keten was absent.

Pyrolysis 2. Vinyl ether (VII) was identified in the cold trap (infrared). The total liquid pyrolysate (*a*) was refluxed for 1 hr. with 10% aqueous sodium hydroxide (100 ml.); distillation of the hydrolysate (water-bath) yielded no alcohols (xanthate colour test[19]). A control test with added methanol, under the same conditions, gave a positive result.

Pyrolysis of compounds (II), (III), (VII), (VIII), *and* (IX).

Pyrolysand	(II)	(II)	(II)	(III)	(III)	(III)	(VII)	(VIII)	(IX)
Pyrolysis No.	1	2	3	4	5	6	7	8	9
Temp.	550°	500°	450°	500°	470°	400°	500°	500°	500°
Feed-rate (g./min.)	0·30	0·54	0·70	0·53	0·53	0·44	0·34	0·30	0·34
Wt. pyrolysed (g.)	64·0	35·0	73·1	70·0	20·0	28·0	32·5	47·0	30·0
(*a*) Liquid pyrolysate (g.)	23·3 *	23·6 *	52·6 *	57·8 *	13·3 *	22·2 *	†	‡	‡
(*b*) Gaseous pyrolysate (l.)	16·0	7·5	9·7	8·0	3·1	3·1	9·0	5·7	4·0
Composition (%) of (*b*) :									
CO	41·0	44·5	39·5	59 §	53 §	43·5	48·2	33·9	39·1
CO_2	25·5	22·3	16·5	19 §	22 §	30·9	Nil	Nil	Nil
CH_4	23·9	22·8	31·4	Nil	Nil	Nil	27·4	46·3	49·0
Unsat. hydrocarbons	9·6	10·4	12·6	22 §	25 §	25·6	24·4	19·8	11·9

* Excluding minor amounts of volatile material in cold trap.
† Large volatile fraction in cold trap not weighed.
‡ Acetaldehyde (removed in 2 : 4-dinitrophenylhydrazine trap) and olefin (in cold trap) not weighed.
§ Approximate.

Pyrolysis 3. The liquid pyrolysate (*a*) contained benzoic anhydride (colour reaction[20]); distillation of (*a*) then yielded 7·1 g., b. p. 190—240°, which contained ethylene dibenzoate.

2-Benzoyloxyethyl Vinyl Ether (III).—*Preparation.* Dry sodium benzoate (60 g.), 2-chloroethyl vinyl ether (200 g.), and triethylamine (3 g.) (found to be a better catalyst than diethylamine), when refluxed gently (24 hr.) and filtered, gave 70 g. (87%) of the ether-ester (III), b. p. 138—140°/15 mm. (lit.,[14] 133°/9 mm.).

Attempts to prepare the product (III) by dehydrochlorinating 2-benzoyloxyethyl 2-chloroethyl ether with pyridine, quinoline, or collidine were unsatisfactory.

Pyrolysis 4. The cold trap contained vinyl ether (VII) (infrared) and acetaldehyde. Distillation of the main liquid pyrolysate (*a*) yielded a fraction containing benzoic acid, but no ethylene dibenzoate (contrast Pyrolysis 5). The gaseous pyrolysate (*b*) contained carbon monoxide and dioxide, methane, ethylene, and acetylene, but no propene (infrared). Keten was absent (aniline trap).

Pyrolysis 5. The cold trap contained acetaldehyde and an unsaturated liquid (not positively identified, but probably vinyl ether). Distillation of (*a*) yielded benzoic acid and the following liquid fractions: (i) b. p. 20—60°, (ii) b. p. 60—130°, (iii) b. p. 130—160°, (iv) b. p. 100—110°/15 mm., (v) b. p. 110—140°/15 mm., and (vi) b. p. above 200°/15 mm. Fraction (iv) contained acetophenone (paper chromatography of 2 : 4-dinitrophenylhydrazone[17]); fraction (vi) consisted of ethylene dibenzoate.

Pyrolysis 6. The cold trap contained acetaldehyde. Distillation of (*a*) yielded 3·7 g., b. p. 94°/15 mm. (vinyl benzoate : infrared), a trace of benzoic acid, and unchanged (III).

Vinyl Ether (VII).—*Purification.* Vinyl ether (anæsthetic quality; from May and Baker Ltd.), freed from inhibitor by distillation, had b. p. 28—34°.

Pyrolysis 7. The liquid pyrolysate (*a*) consisted of unchanged vinyl ether (infrared) and acetaldehyde. Liquid (*a*) yielded an immediate precipitate of acetaldehyde 2 : 4-dinitrophenylhydrazone, whereas pure vinyl ether yields this substance only very slowly, as a result of gradual hydrolysis of the ether. The gaseous pyrolysate (*b*) contained carbon monoxide, methane, and acetylene, but no propene (infrared).

n-Butyl Vinyl Ether (VIII).—*Purification.* The ether (from L. Light & Co.) was carefully redistilled, and had b. p. 92—94°.

Pyrolysis 8. Acetaldehyde was identified as in Pyrolysis 7. The cold trap contained an olefinic liquid; treated with bromine, this yielded 1 : 2-dibromobutane, b. p. 162—167° (lit.,[21] 166°). The main liquid pyrolysate (*a*) had b. p. 92—97°, and was unchanged (VIII).

[19] Feigl, "Spot Tests: Vol. II; Organic Applications," Elsevier, Amsterdam, 4th Edn., 1954, p. 130.
[20] Davidson and Newman, *J. Amer. Chem. Soc.*, 1952, **74**, 1515.
[21] Lépingle, *Bull. Soc. chim. France*, 1926, **39**, 741.

There was no evidence of keten (aniline trap), *n*-butyraldehyde, or any other break-down product.

iso*Butyl Vinyl Ether* (IX).—*Purification.* The ether (from L. Light & Co.), carefully redistilled, had b. p. 82°.

Pyrolysis 9. Acetaldehyde was identified as in Pyrolysis 7. The cold trap contained an olefinic liquid; treated with bromine, this yielded 1 : 2-dibromo*iso*butane (9 g.), b. p. 149°, n_D^{16} 1·513 (lit.,[22] b. p. 149—151°, n_D^{20} 1·512). The main liquid pyrolysate (*a*) had b. p. 83°, and was unchanged (IX). There was no evidence of keten (aniline trap), *iso*butyraldehyde, or any other breakdown product.

The authors thank the Assam Oil Co. Ltd. for a maintenance grant (to H. V. R. I.), and Imperial Chemical Industries Limited for a grant.

Technical Chemistry Department, Royal Technical College, Glasgow, C.1. [*Received, March 14th,* 1956.]

[22] Krestinsky, *Ber.*, 1922, **55**, 2757.

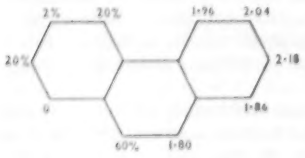
---

688. *Electrophilic Substitution. Part III.* The Nitration of Phenanthrene.*

By M. J. S. Dewar and E. W. T. Warford.

Nitration of phenanthrene in acetic anhydride has been studied under conditions where mononitrophenanthrenes are almost the sole products; the proportions of isomers in this mixture have been determined by isotope analysis. The results are very much at variance with those reported by Schmidt and Heinle,[1] but agree quite well with the relative reactivities predicted [2a] on the basis of molecular-orbital theory.

In the first papers of this series,[2a] Bavin and Dewar drew attention to a serious discrepancy between the predicted reactivities of the various positions in phenanthrene (I) and the proportions of isomers which Schmidt and Heinle [1] had reported for its nitration in hot acetic acid. The reactivity numbers † and proportions of isomers are shown in (I). Bavin and Dewar [2a] were able to show that Schmidt and Heinle's work was unreliable, but their attempts to analyse the mixture of mononitrophenanthrenes by chromatography failed. We have now determined the proportions of isomers quantitatively. Nitration of phenanthrene containing [9-^{14}C]phenanthrene gave almost exclusively a mixture of radioactive mononitrophenanthrenes, which were analysed by isotope dilution analysis, using inactive specimens of the five mononitrophenanthrenes prepared according to Bavin and Dewar.[2b] The nitrations were carried out at three different temperatures, with a large excess of phenanthrene to avoid formation of by-products.[1] Our results are shown in the annexed Table. The proportions of isomers are quite different from those reported by Schmidt and Heinle;[1] in particular the 9- and the 1-position differ little in reactivity, as one would predict from



(I)

Temp. nitration	Proportions of isomers (%) 1-	2-	3-	4-	9-
0°	27·1	4·0	25·4	—	34·2
25	26·2	6·8	21·8	5·6	36·1
35	24·7	5·3	22·9	—	33·4

* Part II, *J.*, 1956, 1441.

† The reactivity number of position 3 was wrongly given as 2·07 in Part I.

[1] Schmidt and Heinle, *Ber.*, 1911, **44**, 1448.

[2] Bavin and Dewar, (*a*) *J.*, 1956, 167; (*b*) 1955, 4477.

the reactivity numbers (see I). Schmidt and Heinle stated that, despite a careful search, they could find no trace of 1-nitrophenanthrene in their nitration product.

The ratio (*ca.* 7) of reactivities at the most reactive (9-) and the least reactive (2-) position is also satisfactory; the difference (0·36) between the reactivity numbers of these positions is almost the same as that (0·31) between the α- and the β-position of naphthalene where the corresponding isomer [3] ratio is about 9.

The 4-position shows a lower reactivity than predicted, but this can reasonably be ascribed to steric hindrance; even in phenanthrene itself there is appreciable hindrance between the 4- and the 5-hydrogen atom. The relatively high reactivity of the 3-position is unexpected and more difficult to explain; part of it could be ascribed to steric hindrance in the α-naphthalenic 1- and 9-position in phenanthrene, as opposed to the lack of hindrance in the β-naphthalenic 3-position.

The proportions of isomers do not seem to vary much with temperature. Unfortunately the proportion of 4-nitrophenanthrene could not be determined directly at 0° and 35° for lack of synthetic material; the synthesis of this isomer is very troublesome.

Experimental

[9-^{14}C]*Phenanthrene.*—The radioactive phenanthrene was prepared from fluorene and $Ba^{14}CO_3$ by Collins's method.[4] 9-Fluorenylmethanol was cyclised very conveniently with hot polyphosphoric acid. The radioactive phenanthrene was diluted with pure phenanthrene to an activity of *ca.* 20,000 counts min^{-1}. $mg.^{-1}$.

Mononitrophenanthrenes.—These were prepared according to Bavin and Dewar.[2b]

Nitration of [9-^{14}C]*Phenanthrene.*—(a) *At* 0°. [9-^{14}C]Phenanthrene (10·353 g.; 18,150 counts $min.^{-1}$ $mg.^{-1}$) was dissolved in redistilled acetic anhydride (500 ml.) at 0°. A solution of nitric acid (0·5 ml.; *d* 1·5) in acetic anhydride (20 ml.), cooled to 0°, was added during 10 min. with stirring. Stirring was continued at 0° for 8 hr., and the solution was then hydrolysed with water (3 l.) containing sulphuric acid (4 ml.). The pale yellow crystalline residue was isolated with chloroform and chromatographed from light petroleum (b. p. 40—60°). The mononitrophenanthrene fraction was eluted with ether, and the chromatographic purification then repeated twice. The first runs from the columns gave unchanged phenanthrene (9·913 g.). The mixed mononitrophenanthrenes (0·152 g.) were used for isotope dilution analysis. The only other product was a trace of coloured material which adhered strongly to alumina.

(b) *At* 25°. Nitric acid (0·25 ml.; *d* 1·5) in acetic anhydride (5 ml.) was added during 4 min. to a well-stirred solution of phenanthrene (9·552 g.; 18,150 counts $min.^{-1}$ $mg.^{-1}$) in acetic anhydride (300 ml.) at 25°, and the mixed mononitrophenanthrenes (0·374 g.) isolated as above.

(c) *At* 35°. The nitration was carried out as at 25°, with similar volumes of nitric acid and acetic anhydride, and 9·809 g. of phenanthrene; the mixed mononitrophenanthrenes weighed 0·622 g. In this case appreciably more of the coloured by-product was formed than at the lower temperature.

Estimation of Radio-carbon.—The specific activities of samples of [9-^{14}C]phenanthrene and the isomers obtained by nitration were found by converting the organic compound into carbon dioxide by the Van Slyke wet combustion method.[5] The active carbon dioxide was introduced into a Geiger–Müller gas-counting tube containing argon and ethanol, and the filling was counted in the Geiger region.[6]

A modified Van Slyke mixture (potassium iodate omitted) generally gave consistent values of carbon dioxide (based on theoretical yield) of $\pm 96\%$ for 2—5 mg. samples which had been boiled gently for 4 min. at <1 mm. It was noticed, however, that 9-nitrophenanthrene required a longer combustion period and also gave a greater percentage spread when counted. It is possible that the carbon attached to the nitro-group is not split off with ease, and, should it be radioactive (as in the 9-isomer), a considerable error will result.

The Geiger–Müller gas-counting tubes (50 ml.; 20th Century Electronics Ltd.) had satisfactory characteristics at low pressures of carbon dioxide when filled with argon (3·0 cm.) and ethanol (1·5 cm.). At 1 cm. of carbon dioxide (used in these experiments) a plateau of 200—280 v with a slope of 5% per 100 v was obtained. Maximum consistency was achieved by making a rough determination of the plateau for each sample and counting at 100 v above the starting

[3] Dewar and Mole, *J.*, 1956, 1441.
[4] Collins, *J. Amer. Chem. Soc.*, 1948, **70**, 2418.
[5] Van Slyke and Folch, *J. Biol. Chem.*, 1940, **136**, 509.
[6] Broda and Feldstein, *Nature*, 1951, **168**, 4275.

voltage (approx. 1150 v). The apparatus and counting tubes were kept in an atmosphere of inactive carbon dioxide when idle, to avoid memory effects.

Isotope Dilution Analysis.—The mixture of mononitrophenanthrenes from a nitration was dissolved in acetone. Portions of the solution were used for analysis for individual isomers. The weighed residue left on evaporation was diluted with a weighed quantity (about four times its weight) of a synthetic inactive isomer, and a pure specimen of the isomer recovered from the mixture by repeated recrystallisation from ethanol. Recrystallisation was continued until the radioactivity of the sample was constant; about ten recrystallisations were normally sufficient. The complete analysis of the 25° nitration product (see Table) shows this procedure to have been sufficient; radioactive contamination would lead to a high estimate for the concentration of a given isomer, but the sum of the individual percentages is less than 100%. Fuller details of the combustion of samples and of the method of isotope dilution analysis are given elsewhere.[7]

QUEEN MARY COLLEGE (UNIVERSITY OF LONDON),
MILE END ROAD, LONDON, E.1. [*Received, March 16th*, 1956.]

[7] Warford, M.Sc. Thesis, London, 1954; Ph.D. Thesis, London, 1956.

---

689. *Electrophilic Substitution. Part IV.* The Nitration of Diphenyl, Chrysene, Benzo*[a]*pyrene,† and Anthanthrene.*

By M. J. S. DEWAR, T. MOLE, D. S. URCH, and E. W. T. WARFORD.

Diphenyl, chrysene, benzo[*a*]pyrene, and anthanthrene have been nitrated by nitric acid in acetic anhydride. The results are compared with the predictions of a molecular-orbital treatment.[1-2] The ratio of isomers formed by nitration of diphenyl has been determined spectrophotometrically. It has been established that chrysene and benzo[*a*]pyrene each yield more than one isomer on nitration. Anthanthrene has been substituted for the first time; two nitro-compounds are described, and their possible structures are discussed.

BELL, KENYON, AND ROBINSON [3] nitrated diphenyl (100 g.) with fuming nitric acid in acetic acid at 70—90°. They separated the 2- (35—39 g.) and 4-nitrodiphenyl (60—70 g.) by making use of the greater solubility of the former in cold ethanol. Jenkins, McCullough, and Booth [4] identified 57% of the crude product of nitration in sulphuric acid as 4-nitrodiphenyl and 34% as 2-nitrodiphenyl. We have nitrated diphenyl in cold acetic anhydride, using excess of the hydrocarbon. The mixture of nitrodiphenyls formed was isolated chromatographically. From a comparison of the ultraviolet spectrum of the mixture with the spectra of the pure isomers, obtained from the mixture by fractional crystallisation, we conclude that the ratio of 2- to 4-nitrodiphenyl = 3·3 : 1.

Nitration of chrysene yielded largely 6-nitrochrysene, the only isomer previously recorded.[5,6,7] We were, however, able to demonstrate that at least one other isomer is also formed.

Windaus and Rennhak [8] nitrated benzo[*a*]pyrene in benzene–acetic acid using a great excess of nitric acid, appreciable dinitration no doubt occurring. Fieser and Hershberg [9] and Creech [10] repeated the work using much less nitric acid. All these authors reported

* Part III, preceding paper.

† Hydrocarbons are numbered as recommended in the "Ring Index." Benzo[*a*]pyrene has often been referred to as 3 : 4-benzopyrene.

[1] Dewar, *J. Amer. Chem. Soc.*, 1952, **74**, 3341 *et seq.*
[2] Bavin and Dewar, *J.*, 1956, 164.
[3] Bell, Kenyon, and Robinson, *J.*, 1926, 1239.
[4] Jenkins, McCullough, and Booth, *Ind. Eng. Chem.*, 1930, **22**, 31.
[5] Schmidt, *J. prakt. Chem.*, 1874, **9**, 281.
[6] Bamberger and Bundorf, *Ber.*, 1890, **23**, 2433.
[7] Newman and Cathcart, *J. Org. Chem.*, 1940, **5**, 618.
[8] Windaus and Rennhak, *Z. physiol. Chem.*, 1937, **249**, 256.
[9] Fieser and Hershberg, *J. Amer. Chem. Soc.*, 1939, **61**, 1564.
[10] Creech, *ibid.*, 1941, **63**, 576.

the isolation of only one isomer, 6-nitrobenzo[*a*]pyrene. We have now shown that nitration in cold acetic anhydride yields in addition certainly one and probably two other isomers.

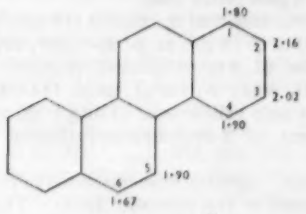
Nitration of anthanthrene in acetic anhydride yielded two mononitro-compounds of unknown structure. One was reduced to the corresponding amine by Dewar and Mole's method.[11]

Discussion.—The success of the molecular-orbital treatment (see Part VI, p. 3581) in accounting for the relative reactivities of hydrocarbons on nitration and for the distribution of the isomeric products prompts us to suggest structures for the new compounds described here, using the calculated reactivity numbers as a basis. The reactivity numbers [1,2] of chrysene (I), benzo[*a*]pyrene (II), and anthanthrene (III) are as shown below.

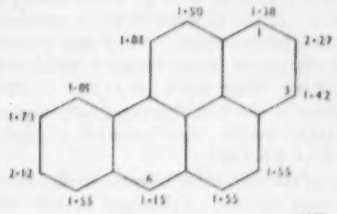
The 6-position is known to be the most reactive in chrysene; the 1-position should be the second most reactive. Since all other points of attack either have high reactivity numbers or, in the case of the 4- and the 5-position, are sterically hindered, we are able to suggest that the second nitrochrysene (m. p. 205—208°) described will prove to be 1-nitrochrysene.

The 6-position should be the most reactive in benzo[*a*]pyrene. Next in order of reactivity should come the 1- and the 3-position. Examination of Fig. 1 in Part VI of this series reveals that the 1- and the 3-isomer should each make up *ca.* 10% of the nitration product. It seems fairly certain, therefore, that the second isomer (m. p. 250—252°) isolated in our experiment was either 1- or 3-nitrobenzo[*a*]pyrene, and that it was initially contaminated by comparable quantities of the other isomer.

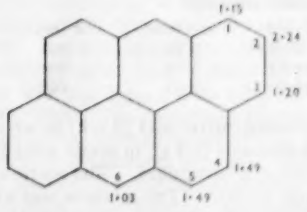
In anthanthrene the 1-, 3-, and 6-positions should be of comparable reactivity. We



(I)



(II)



(III)

have isolated two mononitro-compounds. Some clue as to the structure of the compounds is provided by the colour changes which they show in concentrated sulphuric acid. By analogy with the behaviour of perylene derivatives in sulphuric acid, we might expect 6-nitro- and 6-amino-anthanthrene to be degraded, giving green solutions of anthanthrone. On the other hand we should expect 1- and 3-nitroanthanthrene, if degraded, to yield red solutions of the corresponding nitroanthanthrones (4-nitroanthanthrone [12] is known to give a red solution in sulphuric acid). The evidence suggests that the brown *x*-nitroanthanthrene is the 6-isomer. *y*-Nitroanthanthrene would then be the 1- or the 3-isomer. It is notable that the ease of chromatographic separation of *x*- and *y*-nitroanthanthrene

[11] Dewar and Mole, *J.*, 1956, 2556.
[12] Corbellini and Atti, *Chimica e Industria*, 1936, **18**, 295.

is equalled only by the great facility with which 6-nitrobenzo[*a*]pyrene (a "*meso*"-isomer, comparable with 6-nitroanthanthrene) was separated from the supposed 1- and 3-nitrobenzo[*a*]pyrene.

Experimental

Some microanalyses were carried out by Imperial College microanalytical laboratory. Peter Spence type "H" alumina (100—200 mesh) was used for chromatography. Solvents for chromatography were distilled.

Materials.—Diphenyl (from British Drug Houses Ltd.; m. p. 69·5—70·5°), benzo[*a*]pyrene (from Messrs. Lights; m. p. 176—177°), nitric acid (*d* 1·5) (from British Drug Houses Ltd.), and acetic anhydride (from May and Baker Ltd.) were not purified before use. Chrysene was purified by chromatography and recrystallisation from benzene–light petroleum.

Anthanthrone, prepared from 1 : 1′-dinaphthyl-8 : 8′-dicarboxylic acid [13] (kindly presented by Imperial Chemical Industries Limited, Dyestuffs Division), was reduced to anthanthrene by Clar's method.[14] The hydrocarbon was purified by chromatography from benzene.

Nitration of Diphenyl.—Fuming nitric acid (1·4 ml.) in ice-cold acetic anhydride (20 ml.) was added slowly to a solution of diphenyl (7·70 g.) in acetic anhydride (250 ml.) at 0°. After 24 hr. the anhydride was hydrolysed in water (2 l.) containing sulphuric acid (2 ml.). The mixture was extracted with chloroform. The extract was washed with potassium hydrogen carbonate solution, dried (Na_2SO_4), and evaporated. The residue was chromatographed in light petroleum (b. p. 40—60°) on alumina (20 × 3 cm.). Elution with light petroleum was continued until the front of the yellow nitro-compound had been washed three-quarters of the way down the column. The yellow band was then eluted with ether; the residue from the ether eluate was chromatographed six times more in the above manner in order to get rid of all unchanged diphenyl and traces of quinones. The mixture of nitro-compounds so obtained was a yellow oil (3·07 g.) which slowly set to a pale yellow solid.

Part (2·2 g.) of the mixture of nitro-compounds was dissolved in ethanol (10 ml.) at 60° and cooled to room temperature. Very pale yellow needles (0·58 g.), m. p. 98—108°, crystallised; two recrystallisations from ethanol yielded needles of 4-nitrodiphenyl (Found: C, 72·3; H, 4·7; N, 6·95. Calc. for $C_{12}H_9O_2N$: C, 72·35; H, 4·55; N, 7·0%), m. p. 114—115°. The mother-liquors of the first recrystallisation yielded a pale yellow solid (1·59 g.), m. p. 30—35°; recrystallisation twice from ethanol yielded prisms of 2-nitrodiphenyl (Found: C, 72·3; H, 4·6%), m. p. 34—36°.

Analysis of the mixture of isomers formed by nitration. Spectra were measured in *cyclo*hexane. Beer's law was obeyed. Specimen results are quoted in the annexed Table. These results indicate that the mixture contains 23 ± 1% of the 4-isomer.

	$10^{-3}\varepsilon$ for *x*-nitrodiphenyl				$10^{-3}\varepsilon$ for *x*-nitrodiphenyl		
λ (mμ)	*x* = 2	*x* = 4	mixture	λ (mμ)	*x* = 2	*x* = 4	mixture
320	1·62	8·88	3·23	290	2·86	16·06	5·99
310	2·36	14·11	5·04	280	2·63	12·63	5·05
300	2·85	16·76	6·11	240	13·11	3·96	11·03

Nitration of Chrysene.—Fuming nitric acid (2 ml.) in ice-cold acetic anhydride (10 ml.) was added slowly to a solution of chrysene (1·2 g.) in acetic anhydride (2 l.) at 0°. The solution was stirred at 0° for 2 hr., then left at 2° overnight. The acetic anhydride was hydrolysed in water (2 l.) containing sulphuric acid (2 ml.). The mixture was extracted with chloroform, and the extract was washed with potassium hydrogen carbonate solution. The chloroform was distilled off; the residue was chromatographed in benzene on alumina (24 × 4 cm.) which was washed with 1 : 1 benzene–light petroleum (b. p. 40—60°) to remove chrysene. When the yellow nitrochrysene band had moved three-quarters of the way down the column, it was eluted with 1 : 1 benzene–ether. The residue from the latter eluate was chromatographed four times more in this manner, finally yielding nitrochrysenes as a partly crystalline, yellow solid (0·454 g.) (Found: C, 78·7; H, 4·3; N, 5·1. Calc. for $C_{18}H_{11}O_2N$: C, 79·1; H, 4·1; N, 5·1%), m. p. 165—185°. Part (0·224 g.) of the mixture of nitrocompounds was recrystallised twice from benzene, giving needles of 6-nitrochrysene (Found: C, 78·4; H, 4·1; N, 5·3%), m. p. 206·5—208·5° (64% recovery). Ultraviolet spectrum (in EtOH): $\lambda_{max.}$ 218, 259, 370 mμ ($\log_{10}\varepsilon$ 4·19, 4·45, 3·60); $\lambda_{min.}$ 234, 318 mμ ($\log_{10}\varepsilon$ 4·10, 3·36).

[13] Kalb, *Ber.*, 1914, **47**, 1724.
[14] Clar, *Ber.*, 1939, **72**, 1645.

The mother-liquors from the recrystallisations were chromatographed on alumina (5 × 1 cm.) from 1 : 1 benzene–light petroleum. The first fractions yielded unchanged chrysene and later fractions yielded more 6-nitrochrysene. The tail of the yellow band was eluted with 1 : 1 benzene–ether, giving a solid, m. p. 170—190°, which, recrystallised twice from benzene, had m. p. 205—208°, depressed on admixture with 6-nitrochrysene. This material could not be 6 : 12-dinitrochrysene (lit.,[8] m. p. 380·5—382·5°). Altogether 73% of the mixture of nitrochrysenes was recovered as 6-nitrochrysene of sharp m. p.; this isomer must have comprised *ca.* 90% of the mixture.

Nitration of Benzo[a]*pyrene.*—Fuming nitric acid (0·6 ml.) in ice-cold acetic anhydride (15 ml.) was added to a solution of benzo[*a*]pyrene (0·90 g.) in acetic anhydride (750 ml.) at 0°. The nitration was continued and the nitro-compounds were freed from unchanged hydrocarbon and quinone by-products in a way very similar to that described in the previous experiment. In this case, however, two bands of nitro-compounds were very easily separated chromatographically. The more easily eluted band yielded golden-yellow plates of 6-nitrobenzo[*a*]pyrene (0·601 g.) (Found : C, 80·7; H, 4·0; N, 4·6. Calc. for $C_{20}H_{11}O_2N$: C, 80·7; H, 3·7; N, 4·7%), m. p. 252—253°. Ultraviolet spectrum (in EtOH) : $\lambda_{max.}$ 252, 265, 285, 300, 371, 390, 405 mμ ($\log_{10}\varepsilon$ 4·41, 4·43, 4·27, 4·37, 4·01, 4·09, 3·87), $\lambda_{min.}$ 232, 259, 280, 293, 327, 380, 400 mμ ($\log_{10}\varepsilon$ 4·08, 4·39, 4·17, 4·22, 3·48, 3·93, 3·82). The less easily eluted orange-brown band gave a non-crystalline solid (0·133 g.) (Found : C, 80·5; H, 4·0; N, 4·6%), m. p. 175—210°, which yielded a compound of sharp m. p. only with difficulty; simple recrystallisation from benzene was not very effective. The material was chromatographed from benzene and fractions were taken. The solid residues yielded by the earlier fractions were recrystallised four times from benzene, giving orange needles (Found : C, 80·7; H, 4·1; N, 4·9%), m. p. 250—252°. Ultraviolet spectrum (in EtOH) : $\lambda_{max.}$ 225, 266, 306, 432 mμ ($\log_{10}\varepsilon$ 4·26, 4·54, 4·13, 4·05), $\lambda_{min.}$ 216, 232, 284, 345 mμ ($\log_{10}\varepsilon$ 4·21, 4·14, 4·04, 3·55).

Nitration of Anthanthrene.—Fuming nitric acid in ice-cold acetic anhydride (10 ml.) was added slowly to a solution of anthanthrene (0·248 g.) in acetic anhydride (2 l.) at 0°. The nitration was continued and the nitro-compounds were isolated as in the nitration of chrysene. Two nitroanthanthrene bands were readily separated by chromatography. The more easily eluted brown band gave a crystalline residue (40 mg.), m. p. 253—259°, which was recrystallised twice from benzene, yielding light-brown needles, x-*nitroanthanthrene* (Found : C, 82·4; H, 3·8; N, 4·2. $C_{22}H_{11}O_2N$ requires C, 82·2; H, 3·45; N, 4·4%), m. p. 263—264°. Ultraviolet spectrum (in EtOH) : $\lambda_{max.}$ 231, 256, 329, 415, 439 mμ ($\log_{10}\varepsilon$ 4·51, 4·18, 4·34, 3·85, 3·94), $\lambda_{min.}$ 217, 251, 268, 345, 426 mμ ($\log_{10}\varepsilon$ 4·33, 4·15, 3·80, 3·37, 3·75). The compound gave a red solution in sulphuric acid which became green after 1 hr. at 60°.

The less easily eluted dark red band yielded a red solid (35 mg.) (Found : C, 81·6; H, 3·7; N, 4·3. $C_{22}H_{11}O_2N$ requires C, 82·2; H, 3·45; N, 4·4%), decomp. 210°, of poor crystalline development. The material was chromatographed from benzene and fractions were taken. The residues from the later fractions were recrystallised from benzene giving red needles, *y*-nitroanthanthrene, decomp. 255°. Examination of the other fractions failed to give positive evidence indicating whether or not any other isomer was present. Ultraviolet spectrum (in EtOH) : $\lambda_{max.}$ 232, 314, 405, 429, 478 mμ ($\log_{10}\varepsilon$ 4·55, 4·11, 3·65, 3·96, 4·02), $\lambda_{min.}$ 289, 390, 412, 440 mμ ($\log_{10}\varepsilon$ 3·80, 3·37, 3·59, 3·80). The compound gave a red solution in concentrated sulphuric acid, which did not change colour, even at *ca.* 200°.

Reduction of x-*Nitroanthanthrene.*[11]—Palladised charcoal (5%; 20 mg.) and hydrazine hydrate (2 drops) were added to a solution of *x*-nitroanthanthrene (10 mg.) in ethanol (60 ml.), and the solution was refluxed for 5 min. The solution was filtered. The ethanol and excess of hydrazine hydrate were distilled off and the residue was recrystallised from benzene, giving red needles (Found : N, 4·8. $C_{22}H_{13}N$ requires N, 4·8%), decomp. 210°. Ultraviolet spectrum (in EtOH) : $\lambda_{max.}$ 233, 245, 319, 470 mμ ($\log_{10}\varepsilon$ 4·66, 4·38, 4·37, 3·92), $\lambda_{min.}$ 239, 280, 365 mμ ($\log_{10}\varepsilon$ 4·34, 3·61, 3·01). The amine gave a red solution in concentrated sulphuric acid, which rapidly became green at 30°.

QUEEN MARY COLLEGE (UNIVERSITY OF LONDON),
MILE END ROAD, LONDON, E.1.

[*Received, March 16th,* 1956.]

690. *Electrophilic Substitution. Part V.* Competitive Nitrations.*

By M. J. S. Dewar, T. Mole, and E. W. T. Warford.

Competitive nitrations have been carried out in order to determine the reactivities of several unsubsituted polycyclic aromatic hydrocarbons relative to one another.

A theory which correlates the structure of aromatic hydrocarbons with their reactivity towards substitution must predict, first, the isomeric distribution of substitution products and, secondly, the reactivities of the hydrocarbons relative to one another. This paper, which forms part of a systematic study of the mononitration of polycyclic hydrocarbons by nitric acid in acetic anhydride, deals with the second of these problems. Competitive nitrations of naphthalene and phenanthrene with each other and with benzene, pyrene, triphenylene, and chrysene, and of naphthalene with perylene, benzo[*a*]pyrene, anthanthrene, and coronene, are described. Phenanthrene has also been nitrated in competition with diphenyl.

The competitive method of comparing reaction rates does not require an accurate knowledge of the reaction kinetics, provided we assume that both hydrocarbons are nitrated by the same nitrating agent or agents, and that the rates of nitration are of the first order with respect to the hydrocarbon concentrations. Then, for the reaction of the nitrating agent, X, with hydrocarbons HC_1 and HC_2 at time t, we have

$$\left.\begin{aligned} d[HC_1]_t/dt &= -k_1[X]_t^n[HC_1]_t \\ d[HC_2]_t/dt &= -k_2[X]_t^n[HC_2]_t \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where n is the order of reaction with respect to X. Hence

$$d[HC_1]_t/d[HC_2]_t = k_1[HC_1]_t/k_2[HC_2]_t \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If another nitrating agent, X′, is also active and the ratio k_1'/k_2' of the corresponding rate constants is equal to k_1/k_2, equation (2) still holds.

The justification for the assumptions of the previous paragraph lies in the reproducibility of results. Given the ratios k_1/k_2 and k_1/k_3, we can predict k_2/k_3 correctly to an accuracy of $\pm 50\%$, which is satisfactory as a test of theory in view of the wide experimental range of reactivity ($10^5 : 1$).

Integrating equation (2) from $t = 0$ to $t = T$, the time when the reaction is stopped, we have:

$$k_1/k_2 = (\log_{10}[HC_1]_0 - \log_{10}[HC_1]_T)/(\log_{10}[HC_2]_0 - \log_{10}[HC_2]_T) \quad . \quad . \quad (3)$$

If the only products formed from the hydrocarbons are their nitro-derivatives, equation (3) can be written in the form

$$\frac{k_1}{k_2} = \frac{\log_{10}[HC_1]_0 - \log_{10}([HC_1]_0 - [N_1])}{\log_{10}[HC_2]_0 - \log_{10}([HC_2]_0 - [N_2])} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where $[N_1]$ and $[N_2]$ are the concentrations of the nitro-derivatives of HC_1 and HC_2 respectively. The equation can be written thus reasonably, since under the conditions employed very little quinone is formed as by-product ($<2\%$ in the case of naphthalene,[1] for instance) and since approximately 95% of the material can be recovered as unchanged hydrocarbon and nitro-compounds; no doubt much of the small loss is due to imperfect mechanical handling.

* Part IV, preceding paper.

[1] Dewar and Mole, *J.*, 1956, 1441.

Since the volume in which all reactants and products are contained is constant throughout, equation (4) can be written in the equivalent form

$$\frac{k_1}{k_2} = \frac{\log_{10}(HC_1)_0 - \log_{10}\{(HC_1)_0 - (N_1)\}}{\log_{10}(HC_2)_0 - \log_{10}\{(HC_2)_0 - (N_2)\}} \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where $(HC_1)_0$, etc., represent the molar amounts of substances used or formed in the experiment. The concentration of nitric acid does not enter into this expression and therefore does not need to be known. It is of course necessary to ensure that appreciable amounts of each hydrocarbon remain unchanged; this was the case in each of the experiments described below.

The problem then resolves itself into one of estimating the amounts of the nitro-compounds of each hydrocarbon in the products of the competitive nitrations. In some cases (experiments *a*—*e*) it was possible to separate the nitro-compounds from each other and from the parent hydrocarbons by chromatography and by making use of the low solubilities of the higher hydrocarbons and their nitro-compounds. In the benzene–phenanthrene experiment (*f*) the nitrobenzene was isolated as a mixture with unchanged phenanthrene and was estimated by microdetermination of nitrogen in the mixture. In experiments (*g*—*m*) the nitro-derivatives could not be separated from each other

Hydrocarbon (HC)	$k_{(HC)}/k_{(X)}$ relative to naphthalene	$k_{(HC)}/k_{(X)}$ relative to phenanthrene	Hydrocarbon (HC)	$k_{(HC)}/k_{(X)}$ relative to naphthalene
Benzene *	0·0025	0·0026	Perylene	150
Diphenyl	—	0·042	Benzo[*a*]pyrene	64
Pyrene	29	29	Anthanthrene	290
Triphenylene	4·4	2·3	Coronene	6·9 †
Chrysene	4·1	2·6		

* The volatility of nitrobenzene made it difficult to obtain accurate results for competitive nitrations with benzene.

† At room temperature.

conveniently, but the mixture of nitro-compounds could be separated from the parent hydrocarbons. The compositions of the mixtures and hence the quantities of nitro-compounds formed were determined by analysis or from the radioactivity of the mixtures, by using [9-^{14}C]phenanthrene in the competitive nitrations.[2] In the naphthalene–coronene experiment (*n*) the nitronaphthalenes could be isolated but it was not possible to separate the nitrocoronene from coronene completely. The nitrocoronene was determined as a mixture with coronene by analysis.

It was found that the ratio k(phenanthrene)/k(naphthalene) = 1·3 : 1. The results of the other experiments are summarised in the Table. Their significance will be discussed in a later paper.

In passing we draw attention to an improvement in the Mannich synthesis of triphenylene. This consists in distilling the condensation product and pouring the distillate into acetone, thereby separating dodecahydrotriphenylene from acetone-soluble impurities.

Experimental

Some microanalyses were carried out by Imperial College microanalytical laboratory. Where an analysis has been used to give quantitative results, the figures quoted are the mean of two or more self-consistent determinations.

Peter Spence type "H" alumina was used for chromatography; chromatographic solvents were distilled. Unless otherwise stated, columns were approximately 20 × 4 cm. Where fuller details are not given nitro-compounds were freed from the parent hydrocarbons and quinone by-products by chromatography on alumina from light petroleum (b. p. 40—60°) or benzene–light petroleum until the front of the nitro-compound bands was washed three-quarters of the way down the column. The nitro-compounds were then eluted with ether, which eluted

[2] Dewar and Warford, *J.*, 1956, 3570.

quinones only very slowly. This procedure usually had to be repeated five or six times to remove the last trace of hydrocarbon. The development of the columns could be followed by virtue of the colour of the nitro-compounds and the fluorescence of the hydrocarbons and nitro-compounds under ultraviolet light.

Materials.—Unless otherwise stated, these were from British Drug Houses Limited. Diphenyl (m. p. 69·5—70·5°), pyrene, benzo[*a*]pyrene (from Messrs. Lights; m. p. 176—177°), coronene (kindly given by Imperial Chemical Industries Limited), naphthalene (microanalytical standard), fuming nitric acid (*d* 1·5), and acetic anhydride were not purified before use. Benzene (for molecular-weight determination) was shaken with sulphuric acid to remove thiophen. Phenanthrene was freed from anthracene by treatment with maleic anhydride.[3] Commercial chrysene was purified by chromatography and recrystallisation from benzene–light petroleum. Perylene [4] and anthanthrene [4] were prepared and purified as described earlier.

*Triphenylene.—cyclo*Hexanone (400 ml.) was condensed by Mannich's method.[5] The product was poured into water and extracted with benzene; the extract was distilled. The syrupy fraction, b. p. 160/0·3 mm., was collected, poured into acetone (100 ml.), and stirred, giving dodecahydrotriphenylene (37 g., 10·5%), m. p. 180—210°. Dehydrogenation [6] by 5% palladised charcoal at 400°, followed by chromatography, gave triphenylene (65%), m. p. 190—194°. The m. p. was raised to 195·5—196·5° by decomposition of the recrystallised picrate on an alumina column.

Estimation of [9-^{14}C]*Nitrophenanthrene.*—These estimations were carried out, as described in Part III,[3] by wet combustion to carbon dioxide, which was then counted in a gas-filled Geiger tube containing argon–alcohol. Mononitro-compounds of naphthalene, diphenyl, triphenylene, chrysene, and pyrene were analysed satisfactorily in this manner.

Competitive Nitrations.—(a) *Naphthalene–pyrene.* Fuming nitric acid (0·13 ml.) in ice-cold acetic anhydride (20 ml.) was added to a solution of pyrene (0·636 g.) and naphthalene (8·741 g.) in acetic anhydride (300 ml.) at 0°. The solution was stirred for 2 hr. at 0° and then left overnight at 2°. The acetic anhydride was hydrolysed in water (2 l.) containing sulphuric acid (2 ml.); the mixture was extracted with chloroform (500 ml.), and the extract was washed with water, potassium hydrogen carbonate solution, and water. The chloroform was distilled off, the residue was dissolved in benzene, and the parent hydrocarbons were then removed by chromatography four times from light petroleum containing 5% of benzene. The mixture of nitro-compounds was then taken up in benzene and eluted from a column (12 × 3 cm.), first with light petroleum (2 l.) to remove the last traces of hydrocarbon, then with light petroleum (7 l.) containing 15% of benzene, which eluted nitronaphthalenes (55·9 mg.) (Found: N, 7·9. Calc. for $C_{10}H_7O_2N$: N, 8·1%), and finally with ether (1·5 l.), which removed nitropyrene (99·2 mg.) (Found: N, 5·7. Calc. for $C_{16}H_9O_2N$: N, 5·6%). These weights of products in conjunction with equation (3) lead to the value k(HC)/k(naphthalene) = 29 (see Table). Bavin [7] reports a value 30 : 1.

(b) *Naphthalene–chrysene.* Fuming nitric acid (2 ml.) in ice-cold acetic anhydride (20 ml.) was added to a solution of chrysene (0·546 g.) and naphthalene (1·781 g.) in acetic anhydride (2 l.) at 0°. The nitration was continued as in the previous experiment. After removal of the chloroform, the residue was chromatographed three times from 1 : 1 benzene–light petroleum in order to remove naphthalene and part of the chrysene. The residue from the third column was chromatographed; the column was eluted first with 1 : 1 benzene–light petroleum to remove hydrocarbon and then with ether to remove first the pale yellow band of nitronaphthalenes (contaminated by much chrysene) and then the deeper yellow nitrochrysene band. The residue from the nitrochrysene eluate was chromatographed twice from 1 : 1 benzene–light petroleum (to remove traces of chrysene), yielding nitrochrysenes as a partially crystalline, yellow solid (0·287 g.) (Found: C, 79·1; H, 4·3; N, 5·0. Calc. for $C_{18}H_{11}O_2N$: C, 79·1; H, 4·1; N, 5·0%). The residue from the pale yellow eluate was extracted with ether (2 × 50 ml.). Chrysene was filtered off and the residue from the extract was chromatographed twice from light petroleum containing 10% of benzene, giving nitronaphthalenes as pale yellow crystals (0·363 g.) (Found: N, 8·6%).

(c) *Naphthalene–benzo*[a]*pyrene.* Fuming nitric acid (0·4 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of naphthalene (13·222 g.) and benzo[*a*]pyrene (0·407 g.) in

[3] Bavin and Dewar, *J.*, 1956, 164.
[4] Dewar, Mole, Urch, and Warford, preceding paper.
[5] Mannich, *Ber.*, 1907, **40**, 163.
[6] Diels and Karstens, *Ber.*, 1927, **60**, 2323; Bavin and Dewar, *J.*, 1955, 4479.
[7] Bavin, Ph.D. Thesis, London, 1955.

acetic anhydride (700 ml.) at 0°; the nitration was continued and chromatography was effected as in experiment (*b*). Nitronaphthalene was obtained crystalline (0·170 g.) (Found: N, 7·9%). Two bands of nitrobenzopyrene [4] were separated by chromatography: (i) 6-Nitrobenzo[*a*]pyrene (Ring Index numbering) (0·177 g.) (Found: N, 4·5. Calc. for $C_{20}H_{11}O_2N$: N, 4·7%), m. p. 252—254°; and (ii) an orange solid (0·041 g.) (Found: N, 4·6%), m. p. 175—210°.

(d) *Naphthalene–anthanthrene.* Fuming nitric acid (0·3 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of naphthalene (17·600 g.) and anthanthrene (0·136 g.) in acetic anhydride (1·5 l.) at 0°. The experiment was continued in a way very similar to that described for experiment (b). Nitronaphthalene was isolated crystalline (35 mg.) (Found: N, 7·9%). Two nitroanthanthrene bands were separated by chromatography: (i) brown needles (39 mg.) (Found: N, 4·2. Calc. for $C_{22}H_{11}O_4N$: N, 4·4%); and (ii) a red solid (34 mg.) (Found: N, 4·3%).

(e) *Naphthalene–perylene.* Fuming nitric acid (1 ml.) in ice-cold acetic anhydride was added to a solution of perylene (0·972 g.) and naphthalene (18·052 g.) in acetic anhydride (1·5 l.) at 0°. The experiment was continued as described in experiment (b), giving nitronaphthalenes as pale yellow crystals (0·188 g.) (Found: N, 8·0%) and nitroperylene [1] as red crystals (0·750 mg.), m. p. 208—210° (Found: N, 4·9. Calc. for $C_{20}H_{11}O_2N$: N, 4·7%).

(f) *Benzene–phenanthrene.* Fuming nitric acid (2·5 ml.) in ice-cold acetic anhydride (20 ml.) was added to a solution of benzene (169 g.) and phenanthrene (0·876 g.) in acetic anhydride (600 ml.) at 0°. The solution was stirred at 0° for 2 hr. and then stored at 2° overnight. The acetic anhydride was hydrolysed in water (2 l.) containing sulphuric acid (2 ml.), and the mixture was extracted with light petroleum (b. p. 40—60°; 500 ml.). The extract was washed with potassium hydrogen carbonate solution and dried (Na_2SO_4). All except 50 ml. of the solvent was distilled through a Dixon gauze ring column, and the residue was chromatographed. The column was eluted first with light petroleum (400 ml.) to remove benzene, next with 1 : 1 light petroleum–ether (350 ml.) to remove nitrobenzene, phenanthrene, and, probably, a little benzene, and finally with ether (500 ml.) to remove nitrophenanthrenes (0·192 g.) (Found: N, 6·2. Calc. for $C_{12}H_9O_2N$: N, 6·2%). As much of the solvent as possible was distilled from the second eluate; microanalysis of the residue (0·971 g.) (Found: N, 1·7, 1·8, 1·9%) indicated a nitrobenzene content of 0·151 g.

(g) *Phenanthrene–*[9-^{14}C]*diphenyl.* Fuming nitric acid (0·4 ml.) in ice-cold acetic anhydride (30 ml.) was added to a solution of [9-^{14}C]phenanthrene (0·955 g.; 17,240 counts min.$^{-1}$ mg.$^{-1}$) and diphenyl (6·293 g.) in acetic anhydride (300 ml.) at 0°. The acetic anhydride was hydrolysed in water (3 l.) containing sulphuric acid (5 ml.); the mixture was extracted with chloroform (500 ml.), and the extract was washed with potassium hydrogen carbonate solution and dried (Na_2SO_4). The chloroform was distilled and the residue was chromatographed six times from light petroleum, yielding a pale yellow paste of mixed nitro-compounds (0·331 g., 11,150 counts min.$^{-1}$ mg.$^{-1}$, indicating a nitro[9-^{14}C]phenanthrene content of 0·253 g.; the sample of the mixture for combustion was weighed as an oil in order to ensure homogeneity).

(h) [9-^{14}C]*Phenanthrene–pyrene.* Fuming nitric acid (0·2 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of [9-^{14}C]phenanthrene (4·784 g.; 5709 counts min.$^{-1}$ mg.$^{-1}$) and pyrene (0·398 g.) in acetic anhydride (250 ml.) at 0°. The experiment was continued as in experiment (g); after chromatography 5 times from 1 : 4 benzene–light petroleum, a mixture of nitropyrene and nitrophenanthrenes was obtained as a golden-yellow, partially crystalline solid (0·526 g.) (1802 counts min.$^{-1}$ mg.$^{-1}$, indicating a nitrophenanthrene content of 0·210 g.).

(i) [9-^{14}C]*Phenanthrene–chrysene.* Fuming nitric acid (1·5 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of chrysene (0·508 g.) and phenanthrene (1·777 g.; 5709 counts min.$^{-1}$ mg.$^{-1}$) in acetic anhydride (1·3 l.) at 0°. Treatment of the product as in experiment (h) yielded the mixture of nitro-compounds as a pale yellow solid (0·564 g.; 2322 counts min.$^{-1}$ mg.$^{-1}$, indicating a nitrophenanthrene content of 0·287 g.).

(j) [9-^{14}C]*Phenanthrene–triphenylene.* Fuming nitric acid (0·6 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of phenanthrene (2·751 g.; 7800 counts min.$^{-1}$ mg.$^{-1}$) and triphenylene (0·941 g.) in acetic anhydride (400 ml.) at 0°. The solid mixture of nitro-compounds (0·923 g.; 3710 counts min.$^{-1}$ mg.$^{-1}$, indicating a nitrophenanthrene content of 0·550 g.) was isolated as in experiment (g). (The sample for combustion was weighed as an oil to ensure homogeneity.)

(k) [9-^{14}C]*Phenanthrene–naphthalene.* Fuming nitric acid (0·3 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of naphthalene (0·980 g.) and phenanthrene (1·061 g.; 5709 counts min.$^{-1}$ mg.$^{-1}$) in acetic anhydride (200 ml.) at 0°. The experiment was continued as in experiment (g); chromatography five times from light petroleum containing 10% of

benzene yielded the mixed nitro-compounds as a pale yellow oil (0·670 g.; 2523 counts min.$^{-1}$ mg.$^{-1}$, indicating a nitrophenanthrene content of 0·372 g.).

A similar experiment with non-radioactive phenanthrene gave nitronaphthalene and nitrophenanthrene which was analysed for nitrogen. The value of k/k_1, 1·4, was in good agreement with that (1·3) quoted on p. 3577.

(l) *Naphthalene–benzene.* Fuming nitric acid (2·5 ml.) in ice-cold acetic anhydride (20 ml.) was added to a solution of benzene (130 g.) and naphthalene (0·956 g.) in acetic anhydride (300 ml.) at 0°. The nitration was continued and a solution of the product in light petroleum (b. p. 40—60°) was prepared as in experiment (f). All except 50 ml. of the solvent was distilled through a Dixon gauze column. The residue was chromatographed five times from light petroleum (1·3 l.) (b. p. 40—60°) on alumina (20 × 4 cm.) to remove naphthalene and benzene. The final ether eluate yielded a yellow oil (0·736 g.) (Found: C, 65·5; H, 4·3; N, 9·15%). Comparison of these figures with experimental analyses for nitronaphthalenes (Found: C, 69·7; H, 4·3; N, 8·3. Calc. for $C_{10}H_7O_2N$: C, 69·4; H, 4·1; N, 8·1%) and nitrobenzene (Found: C, 58·8; H, 4·3; N, 11·4. Calc. for $C_6H_5O_2N$: C, 58·5; H, 4·1; N, 11·4%) indicated that the mixture contained 33% of nitrobenzene. Experimental, rather than calculated, analyses were used in order that systematic errors in isolating the nitro-compounds and in analyses might be removed.

(m) *Naphthalene–triphenylene.* Fuming nitric acid (0·5 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of naphthalene (4·008 g.) and triphenylene (1·425 g.) in acetic anhydride (1·2 l.) at 0°. The experiment was continued as in experiment (g); chromatography five times from light petroleum containing 5% of benzene yielded the mixture of nitro-compounds as a yellow oil (1·034 g.) (Found: C, 75·0; H, 4·4; N, 6·7%). Comparison of these figures with experimental analyses for samples of nitronaphthalenes (Found: C, 69·7; H, 4·3; N, 8·3%) and nitrotriphenylenes (Found: C, 79·1; H, 4·3; N, 5·3. Calc. for $C_{18}H_{11}O_2N$: C, 79·1; H, 4·1; N, 5·1%), isolated by methods similar to the above, indicated that the mixture contained 45·8% of nitronaphthalenes.

(n) *Naphthalene–coronene.* Fuming nitric acid (3 ml.) in ice-cold acetic anhydride (10 ml.) was added to a solution of coronene (0·216 g.) and naphthalene (0·407 g.) in acetic anhydride (2 l.) at 23°. After 24 hr. the acetic anhydride was hydrolysed; the mixture was extracted with chloroform and the extract was washed with potassium hydrogen carbonate solution. The chloroform was distilled off and the light brown residue was extracted several times with ether (50 ml.). The ether was removed and the yellow residue was chromatographed four times from light petroleum, yielding crystalline nitronaphthalenes (80 mg.) (Found: N, 7·95%). The ether-insoluble material was chromatographed; no separation of bands was observed. The whole of the band was therefore eluted with benzene–ether, and the solvent removed, leaving a yellow residue (205 mg.) (Found: C, 86·55; H, 3·7; N, 3·4. Calc. for $C_{24}H_{12}$: C, 96·0; H, 4·0. Calc. for $C_{24}H_{11}O_2N$: C, 83·5; H, 3·5; N, 4·1%). Analysis indicated that the residue contained 20% of coronene and 80% of nitrocoronene.

The mixture (80 mg.) was recrystallised twice from benzene, giving golden-yellow needles of nitrocoronene (40 mg.), m. p. >360° (Found: C, 83·0; H, 3·5; N, 4·1%). Ultraviolet spectrum (in EtOH): $\lambda_{max.}$ (mμ) 390, 330, 300, 215 ($\log_{10}\varepsilon$ 3·30, 3·57, 3·82, 3·71.), $\lambda_{min.}$ 370, 323, 250 ($\log_{10}\varepsilon$ 3·27, 3·56, 3·34).

QUEEN MARY COLLEGE (UNIVERSITY OF LONDON),
MILE END ROAD, LONDON, E.1.

[*Received, March 16th*, 1956.]

691. *Electrophilic Substitution. Part VI.* The Nitration of Aromatic Hydrocarbons; Partial Rate Factors and their Interpretation.*

By M. J. S. Dewar, T. Mole, and E. W. T. Warford.

The work on aromatic nitration described in the five preceding papers of this series is reviewed, and partial rate factors are shown to correspond closely to the predictions of the molecular-orbital theory. The relative reactivities of hydrocarbons also run parallel to those for methylation and trichloromethylation by radicals. The nature of the transition state in aromatic substitution and its correlation with reactant structure are discussed.

For reasons outlined in the first paper [1] of this series, aromatic substitution is a suitable reaction for testing theories of chemical reactivity; a preliminary survey indicated that useful data could be obtained from a study of the nitration of hydrocarbons by nitric acid in acetic anhydride.

In Part V [5] we described a study of the relative reactivities of a number of such hydrocarbons by the competitive method, and in the other Parts [1-4] we reported the proportions of isomers found by the nitration of individual hydrocarbons under standard conditions. From these data we have calculated the partial rate factors, shown in the Table, for nitration at various positions in the different hydrocarbons.

Hydrocarbon	Position [a]	Partial rate factor [b]	Reactivity number [c]
Benzene	—	1	2·31
Diphenyl	2	30	2·07
Diphenyl	4	18	2·07
Naphthalene	1	470	1·81
Naphthalene	2	50	2·12
Phenanthrene	1	360	1·86
Phenanthrene	2	92	2·18
Phenanthrene	3	300	2·04
Phenanthrene	4	79	1·96
Phenanthrene	9	490	1·80
Pyrene	1	17,000	1·51
Triphenylene [1, 2]	1	600	2·00
Triphenylene	2	600	2·12
Chrysene	2	3500	1·67
Perylene	3	77,000	1·34
Benzo[*a*]pyrene	6	108,000	1·15
Coronene	—	1150	1·80
Anthanthrene	6(?)	156,000	1·03

[a] " Ring Index " numbering. [b] Allowance is made for the number of positions of each type. [c] The reactivity numbers were found by the method described previously (Dewar, *J. Amer. Chem. Soc.*, 1952, **74**, 3341 *et seq.*) and agree, with two minor exceptions, with the values listed there.

A commonly accepted theory of aromatic substitution is that first proposed by Wheland.[6] He assumed that the annular carbon atom, i, undergoing attack changes its hydridisation, becoming tetrahedral in the transition state and so being removed from conjugation with the remainder of the aromatic system. In the transition state both the reagent, X, and the hydrogen atom being replaced are attached to this carbon atom by normal σ-bonds. If entropy effects can be neglected, the velocity constant, k_i, is given by the equation:

$$\log k_i = A_X - (\delta E_\pi)_i/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where A_X is a constant characteristic of the reagent, X, and $(\delta E_\pi)_i$ is the change in conjugation energy of the aromatic system when atom i is removed from it.

* Part V, preceding paper.

[1] Bavin and Dewar, *J.*, 1956, 164.
[2] Dewar and Mole, *J.*, 1956, 1441.
[3] Dewar and Warford, *J.*, 1956, 3570.
[4] Dewar, Mole, Urch, and Warford, *J.*, 1956, 3572.
[5] Dewar, Mole, and Warford, *J.*, 1956, preceding paper.
[6] Wheland, *J. Amer. Chem. Soc.*, 1942, **64**, 900.

For substitution in an even alternant hydrocarbon, the Wheland transition state is an odd alternant hydrocarbon. For this case it can be shown [7] that we can, as an approximation, re-write equation (1) in the form :

$$\log k_i = A_X + 2\beta(a_{ir} + a_{is})/RT$$
$$= A_X + \beta N_i/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

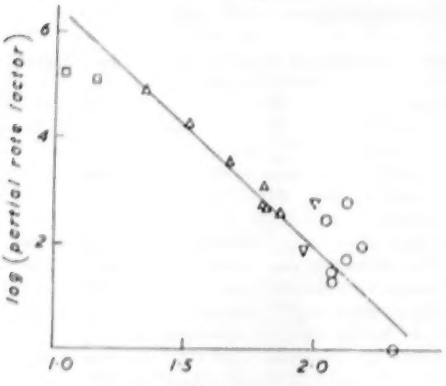
where β is the carbon–carbon resonance integral, and a_{ir} and a_{is} are the coefficients of the atomic orbitals of the atoms r and s, adjacent to atom i in the non-bonding molecular orbital of the transition state. The rate of reaction is therefore determined by the quantity $2(a_{ir} + a_{is})$ which is termed [1] the reactivity number (N_i) of the atom i.

It follows that

$$\log k_i/k_o = \beta(N_i - N_o)/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

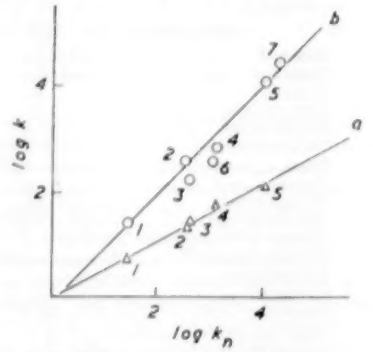
where k_o and N_o are the corresponding values for benzene. Fig. 1 shows a plot of $\log_{10} k_i/k_o$, calculated from the data in the Table, against the corresponding reactivity numbers.[7, 8]

FIG. 1. *Plot of* $\log_{10}(k_i/k_a)$ *against* N_i *for nitration of hydrocarbons by nitric acid in acetic anhydride.*



□ 9-*Anthryl positions.*
△ α-*Naphthyl positions.*
▽ 4-*Phenanthryl positions.*
○ *Other positions.*

FIG. 2. *Plot of (a)* $\log_{10} k_M$ *and (b)* $\log_{10} k_T$ *against* $\log_{10} k_N$.



1, *Diphenyl.* 5, *Pyrene.*
2, *Naphthalene.* 6, *Triphenylene.*
3, *Phenanthrene.* 7, *Benzo[a]pyrene.*
4, *Chrysene.*

The points lie reasonably well on a straight line. This test of the theory is quite severe since the observed values of k_i cover a range of $10^5 : 1$. Agreement is not perfect; the graph suggests that benzene ought to be four times as reactive as we have found, and that triphenylene is about four times more reactive than it ought to be if equation (3) held accurately. The most serious anomaly is the failure to find any 4-nitropyrene in the nitration of pyrene, since the 4-position has a reactivity number of 1·68.

Differences in steric factors do not appear to influence the partial rate factors for nitration greatly. Reactivities at positions of α-naphthalenic type lie very close to the line in Fig. 1. Those of the more hindered positions of the 9-anthryl type lie consistently below the line and those of the less hindered β-napthalenic positions lie above it, as we would expect. In the nitration of triphenylene approximately equal amounts of 1- and 2-nitrotriphenylene were found.[1,9] This suggests that a 4-phenanthryl type of position is subject

[7] Dewar, *J. Amer. Chem. Soc.*, 1952, **74**, 3341 *et seq.*
[8] Bavin, Ph.D. Thesis, London, 1955.
[9] Barker, Emmerson, and Periam, *J.*, 1955, 4482.

to steric hindrance as compared with a β-naphthalenic type; in this case the steric hindrance is sufficient to affect the ratio of partial rate factors by a factor of 3. The effect seems to be more important for bromination, the only product from triphenylene being its 2-bromo-derivative.[9]

According to the simple molecular orbital treatment, the relative reactivities of even alternant hydrocarbons should be independent of the substituting agent. Partial rate factors should, therefore, be the same for all types of substitution. This prediction cannot be tested directly since no equivalent data are available for other reactions. However, Levy and Szwarc [10] determined the relative reactivities of hydrocarbons towards free methyl radicals, and Kooyman and Farenhorst [11] studied similar reactions with trichloromethyl radicals. Although the products have not been characterised, there seems little doubt [10] that these reactions proceed through intermediates or transition states of the Wheland type. If the reactivity of a given hydrocarbon relative to benzene is k_N, k_M, and k_T for nitration, methylation, and trichloromethylation, respectively, then we should find that $k_N = k_M = k_T$. This, in fact, is not the case, but Fig. 2 shows that there are linear relations between $\log_{10} k_N$ and $\log_{10} k_M$ and between $\log_{10} k_N$ and $\log_{10} k_T$. Levy and Szwarc [10] had already pointed out the correspondence between their results and those of Kooyman and Farenhorst; we have taken the value which they suggest for the rate of reaction of benzene with trichloromethyl radicals.

It is evident from equation (2) that the slope of the line in Fig. 1 is equal to $2{\cdot}3\beta/\boldsymbol{R}T$. Moreover it can be seen that if the values of the parameter β are β_N, β_M, and β_T for the three types of reaction, then the slopes of the lines, a and b, in Fig. 2 are given by β_M/β_N and β_T/β_N respectively. In this way we find the values:

$$\beta_N = -6{\cdot}0 \text{ kcal./mole}; \quad \beta_M = -3{\cdot}2 \text{ kcal./mole}; \quad \beta_T = -6{\cdot}0 \text{ kcal./mole} \quad . \quad (4)$$

Now β should be a universal constant for these hydrocarbons and its value can be determined by comparing observed and calculated values for their resonance energies. The appropriate value so found [12] is approximately −20 kcal./mole. The values for β_N, β_M, and β_T therefore seem anomalous not only because β_M differs from β_N and β_T, but also because they are numerically too small.

Now it is true that the value of β quoted above was derived from calculated resonance energies of even hydrocarbons. It is possible that a somewhat different value of β might be more appropriate for odd hydrocarbons—such as the Wheland transition state in subsitution—and in that case equation (2) would no longer hold generally. Such an explanation of the anomaly is unacceptable for three reasons. First, one would not expect a linear relation between $\log_{10} k_i$ and N_i. Secondly, it can be shown very simply that equation (2) would still hold for the relative reactivities of different positions in any one hydrocarbon, and, if so, the observed isomerism requires a low value for β. Thirdly, a theoretical treatment analogous to the above has been given for the S_N1 solvolysis of arylmethyl chlorides in moist formic acid, when the even reactant $R{\cdot}CH_2Cl$ gives rise to a transition state containing the odd ion $R{\cdot}CH_2^+$; in this case Dewar and Sampson [13] were able to correlate the observed and calculated rates by using a value for the carbon–carbon resonance integral of $\beta = -30$ kcal./mole, implying that an analogous value of β can be used for both odd and even systems. (In this case a higher numerical value for β would be expected than the one which we quoted earlier, as Dewar and Sampson [13] have shown.)

All the difficulties would be met if, as suggested by Bavin and Dewar,[1] the structure postulated by Wheland is not a transition state but a stable intermediate. The actual transition state would then be one in which the attacking reagent is still comparatively remote from the atom, i, undergoing substitution, and in which the hybridisation of atom i is not sp^3 but intermediate between sp^2 and sp^3. Then the resonance integrals between atom i and atoms r and s in the transition state would not be zero, but would have some

[10] Levy and Szwarc, *J. Amer. Chem. Soc.*, 1955, **77**, 1949.
[11] Kooyman and Farenhorst, *Trans. Faraday Soc.*, 1953, **49**, 58.
[12] Wheland, *J. Amer. Chem. Soc.*, 1941, **63**, 2025.
[13] Dewar and Sampson, *J.*, 1956, 2789.

value intermediate between zero and the " normal " value, β. If the degree of hybridisation in the transition state depends mainly on the reagent, being similar for any one reagent for attack on any position in any hydrocarbon, equation (2) becomes

$$\log k_i = A_X + (\beta - \beta_X)N_i/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where β_X is the value of the resonance integral between atom i and atoms r and s in the transition state for substitution by X. This can be written in the form

$$\log k_i = A_X + \beta'_X N_i/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where

$$\beta'_X = \beta - \beta_X \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Consequently equation (2) will appear to hold, but β must be replaced by a numerically smaller parameter β'_X, characteristic of the particular reagent, X. Thus the low numerical values of the parameters, β_N, β_M, and β_{Fe} can be explained.

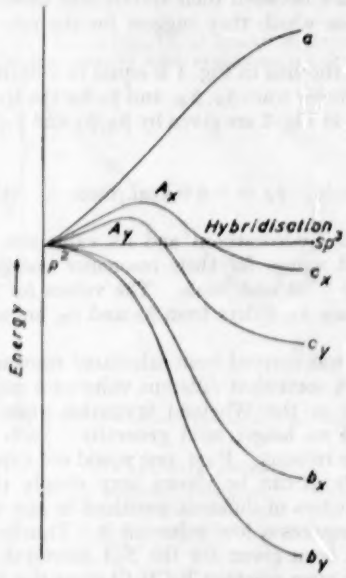


FIG. 3. *Potential energy diagram for substitution by reagents* X *and* Y.

The manner in which β'_X should vary with the reagent, X, can also be predicted in a general way, by using a kind of argument first suggested by Bell.[14] Let us plot the energy of the system against a reaction co-ordinate. Since the reaction involves a steady change of hybridisation of the atom, i, from sp^2 to sp^3 we may take hybridisation as a reaction co-ordinate. In Fig. 3, curve (*a*) represents the change in conjugation energy during the reaction and the curve (b_X) the changes due to formation of the C–X bond, differential solvation effects, etc. The composite curve (c_X) expresses the overall energy of the system, the transition state, A_X, corresponding to the value $\beta = \beta_X$.

Consider now a more exothermic substitution reaction by a reagent, Y. Here curve (*a*) remains the same as in the previous case, but the new curve (b_Y) lies below (b_X), and thus the composite curve (c_Y) below (c_X). It is obvious from the geometry of the Figure that the more exothermic substitution by Y will in general require less activation energy than substitution by X, and that, since it has a hybridisation of more marked sp^2 character,

[14] Bell, " Acid–Base Catalysis," Oxford Univ. Press, 1941.

the transition state, A_Y, will correspond to a numerical value of β_Y greater that that of β_X. Then from equation (7),

$$|\beta'_Y| < |\beta'_X| \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Now considering substitution by X and Y at two hydrocarbon position, m and n, it follows from equation (5) that

$$\log (k_m/k_n)_X = \beta'_X(N_m - N_n)/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

$$\log (k_m/k_n)_Y = \beta'_Y(N_m - N_n)/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where $(k_m/k_n)_X$ and $(k_m/k_n)_Y$ are the ratios of velocity constants for substitution at positions m and n by X and Y respectively. Suppose that $N_m < N_n$, so that $k_m > k_n$, then from equations (8), (9), and (10) we have :

$$(k_m/k_n)_X > (k_m/k_n)_Y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

In other words the ratio of reactivities of the two positions is less for the more reactive reagent. Extension of this argument leads to the rule that the more reactive a substitution agent, X, the lower is the numerical value of β'_X and the less orientational selectivity should the reagent show.

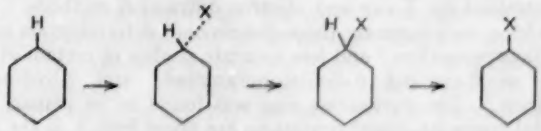
This rule has been deduced empirically by Brown and Nelson [15] for substitution in benzene derivatives. It is a special case of a general phenomenon noted by Dewar.[16] Consider a series of analogous reactions of compound A, in each of which two isomeric products can be formed. Then the greater the ease of reaction, the more nearly equal in general are the amounts of the two products.

The reactions of hydrocarbons with methyl and trichloromethyl radicals confirm this rule. The trichloromethyl radical should be less reactive than the methyl radical, both because of mesomeric stabilisation and because steric repulsion between the chlorine atoms will hinder reactions leading to tetrahedral compound R·CCl_3 (cf. Brown and Fletcher [17]). In fact $\beta_T > \beta_M$, and the spread of reaction rates is greater for trichloromethylation than for methylation, as Fig. 2 shows. Preliminary experiments suggest that the same is true for bromination as compared with nitration; we are studying this and other reactions in detail in order to obtain further evidence.

The observed values of β'_X are very small ($\frac{1}{4}\beta$). This suggests that the transition state in substitution is much closer to the parent aromatic system than to the Wheland structure. We have, however, to consider one more factor; there must be significant hyperconjugation [18] between the tetrahedral group, $>$CHR, of the Wheland structure and the neighbouring aromatic system. Thus equation (2) should be written

$$\log (k_i/k_0) = (\beta - \beta_h)(N_i - N_0)/RT \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where β_h is the effective value of the C_1–C_r and C_1–C_s resonance integrals in the Wheland structure. Although this effect could hardly be large enough to explain our results completely, it does mean that the transition state for substitution must be closer to the Wheland structure than the low value of β'_X would at first sight suggest.



(I) (II)

We have hitherto assumed that even if the structure (II) postulated by Wheland is not the transition state, substitution nevertheless proceeds by way of it as an intermediate.

[15] Brown and Nelson, *J. Amer. Chem. Soc.*, 1953, **75**, 6292; 1955, **77**, 2300 *et seq.*
[16] Dewar, *Discuss. Faraday Soc.*, 1947, **2**, 261.
[17] Brown and Fletcher, *J. Amer. Chem. Soc.*, 1949, **71**, 1845; 1950, **72**, 1223.
[18] Muller, Pickett, and Mulliken, *ibid.*, 1954, **76**, 4770.

Although this idea is very attractive, and probably true, we did not invoke it explicitly in putting forward equation (6), and arguments very similar to those used here would still be applicable if structure (II) were never achieved in the course of the reaction. Our arguments require only the assumption that the transition state is of the type (I), where the C–X bond is comparatively long and weak and the C–H bond is short and strong. Melander [19] has shown that the C–H bond cannot be appreciably stretched in the transition state for the nitration of toluene by the NO_2^+ ion.

With respect to this and the three preceding papers where relevant, we acknowledge maintenance grants from the Ministry of Education (to E. W. T. W.) and from the Department of Scientific and Industrial Research (to T. M. and D. S. U.). We are very grateful to Mrs. R. Barnett and Mr. R. Sampson for their help in preparing this and the two preceding papers.

Queen Mary College (University of London),
Mile End Road, London, E.1. [*Received, March 16th*, 1956.]

[19] Melander, *Nature*, 1949, **163**, 599.

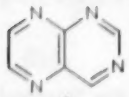
---

692. *The Crystal and Molecular Structure of Pteridine.*

By T. A. Hamor and J. Monteath Robertson.

Pteridine (I) crystallises in the non-centrosymmetric space group $Pna2_1$ with four molecules per unit cell. *X*-Ray analysis shows that the molecule is planar to within 0·06 Å, with standard deviations in co-ordinates of about 0·03 Å. The carbon–nitrogen bond lengths vary between 1·28 and 1·41 Å, and the carbon–carbon lengths between 1·35 and 1·42 Å. These measurements have been compared with molecular-orbital calculations of the bond lengths.

Pteridine (I), which is the parent substance of a large number of naturally occurring compounds of biological importance, is highly unstable, being rapidly decomposed by dilute acid and alkali at room temperature. In solution it is decomposed on exposure to daylight, but the solid, although volatile, can be preserved without much difficulty. In the course of an extensive study of the simpler natural and synthetic pteridines, Albert [1] has found that they are, in general, unstable to acid and alkali unless powerfully electron-donating groups (hydroxyl, amino, etc.) are present, and he has further pointed out that this instability appears to be due to the fact that in pteridine the four ring-nitrogen atoms are competing for the π-electrons contributed by the six carbon atoms. The aromatic stabilisation is therefore much diminished and the pteridine molecule may in consequence be non-planar. Our present *X*-ray investigation of the crystal and molecular structure of pteridine has been undertaken at the suggestion of Professor Albert in order to examine this point and attempt a full determination of the structure and geometry of the molecule.



(I)

No *X*-ray structural investigation of a pteridine or any other azanaphthalene has so far been reported. The related pyrimidine, pyrazine, and purine ring systems have, however, been examined by *X*-ray and electron-diffraction methods. The work on the pyrimidines includes a very accurate three-dimensional determination of the structure of 4-amino-2 : 6-dichloropyrimidine [2] and less accurate studies of certain other trisubstituted derivatives such as 2-amino-4 : 6-dichloropyrimidine [3] and 2-hydroxy-4 : 6-dimethylpyrimidine dihydrate.[4] The pyrimidine ring was found to be planar, within the limits of the experimental errors (standard deviations are about 0·02 Å in the three-dimensional work). For the carbon–carbon and carbon–nitrogen bonds in pyrimidine Clews and Cochran [2] have suggested lengths of 1·38 and 1·33 Å, and angles of 130°, 114°, 124°, and

[1] Albert, Brown, and Cheeseman, *J.*, 1951, 474; 1952, 1620; 1952, 4219; Albert and Brown, *J.*, 1953, 74; Albert, Brown, and Wood, *J.*, 1954, 3832; Mason, *J.*, 1955, 2336; Albert, *J.*, 1955, 2690; Albert, *Quart. Rev.*, 1952, **6**, 197.
[2] Clews and Cochran, *Acta Cryst.*, 1949, **2**, 46.
[3] Clews and Cochran, *ibid.*, 1948, **1**, 4.
[4] Pitt, *ibid.*, 1948, **1**, 168.

114° for NCN, CNC, NCC, and CCC. These values are, however, based on studies of substituted pyrimidines only.

Pyrazine has been examined in the gas phase by electron-diffraction [5] and is reported to have a planar ring. From an *X*-ray crystal investigation using three-dimensional data [6] tetramethylpyrazine is found to be planar with carbon–carbon and carbon–nitrogen bonds of 1·44 and 1·31 Å (mean), and all ring angles within 2° of 120°. In the related structures of melamine [7] and *s*-triazine [8] the rings are apparently planar.

Of substances containing the purine ring system, salts of adenine [9-10] and guanine [11] have been studied, and in both substances the purine ring has been found apparently planar, although not all the atomic co-ordinates could be accurately determined. Carbon–nitrogen bond lengths in adenine vary from 1·30 to 1·38 Å and carbon–carbon from 1·37 to 1·40 Å.

The general conclusion from these results is that the ring systems are planar, although the bonds vary in length. In most cases examined electron-donating substituents have been present, and small deviations from a planar structure would have been difficult to detect. The possibility that the pteridine ring system is non-planar is certainly not excluded.

The results of our present analysis of the pteridine structure are given below. The work has been hampered by the fact that only extremely thin crystals could be prepared. However, nearly half of the possible reflections have been observed with copper radiation in the three principal zones, and by successive two-dimensional refinements the errors have been reduced as far as possible. After allowance for the fact that the structure is non-centrosymmetrical and most of the phase constants are unrestricted, standard deviations in the final bond lengths are about 0·035 Å. The maximum displacement of the ring atoms from a planar structure is found to be 0·06 Å, and the mean displacement 0·025 Å. In view of the comparatively small number of structure factors used, these results cannot be regarded as indicating any significant departure from a strictly planar molecule. The observed carbon–nitrogen bond lengths vary between 1·28 and 1·41 Å, and the carbon–carbon bonds between 1·35 and 1·42 Å. These results have been compared with molecular-orbital calculations of the lengths, and the agreements are found in general to be within the limits of possible error.

Crystal Data.—Pteridine, $C_6H_4N_4$; M, 132·1; m. p. 139°; d, calc. 1·483, found 1·487. Orthorhombic, $a = 24{\cdot}70 \pm 0{\cdot}05$, $b = 3{\cdot}79 \pm 0{\cdot}01$, $c = 6{\cdot}32 \pm 0{\cdot}01$ Å. Volume of the unit cell, 592 Å^3. Absent spectra, $(0kl)$ when $k + l$ is odd, $(h0l)$ when h is odd. Space group, $Pna2_1$ (C_{2v}^9) or $Pnam$ (D_{2h}^{16}). $Pna2_1$ is obtained as a result of this investigation. Four asymmetric molecules per unit cell. Absorption coefficient for *X*-rays ($\lambda = 1{\cdot}54$ Å) $\mu = 9{\cdot}74$ cm.$^{-1}$. Total number of electrons per unit cell $= F(000) = 272$.

Good crystals could only be obtained by vacuum-sublimation and these were in the form of extremely thin yellow plates with (100) prominently developed, and a tendency to elongate in the b axial direction. They are volatile at room temperature and very soluble in most common solvents.

Analysis of the Structure.—It was not found possible to distinguish between the two possible space groups on the basis of polarity tests or from a statistical examination of the intensities.[12] From the chemical structure, the molecule may have a plane of symmetry, and it may also simulate centrosymmetry rather closely. As there are only four molecules in the unit cell, the higher symmetry space group (Pnam) would demand either a molecular plane or a centre of symmetry. Although these cannot be excluded, it is found that the special positions in this space group, together with the cell dimensions and molecular-packing requirements, make any such arrangement of the molecules virtually impossible.

[5] Schomaker and Pauling, *J. Amer. Chem. Soc.*, 1939, **61**, 1769.
[6] Cromer, Ihde, and Ritter, *ibid.*, 1951, **73**, 5587.
[7] Hughes, *ibid.*, 1941, **63**, 1737.
[8] Wheatley, *Acta Cryst.*, 1955, **8**, 224.
[9] Broomhead, *ibid.*, 1948, **1**, 324.
[10] Cochran, *ibid.*, 1951, **4**, 81.
[11] Broomhead, *ibid.*, 1951, **4**, 92.
[12] Wilson, *ibid.*, 1949, **2**, 318; Howells, Phillip, and Rogers, *ibid.*, 1950, **3**, 210.

The lower-symmetry space group, $Pna2_1$, was therefore assumed, with the four molecules in general positions.

As the b axis is only 3·79 Å in length, it is safe to assume that the molecules must lie approximately in the (010) plane, the maximum permitted deviation being about 26° if a van der Waals contact distance of 3·4 Å is to be maintained between the molecular planes. A clue regarding the relative positions of the molecules in the unit cell is provided by the fact that the (*h*00) reflections are only present when $h = 4n$, up to the 24th order. This complete quartering means that the x co-ordinate of the centre of the reference molecule must be rather accurately $a/8$. Similarly, a consideration of the (*hk*0) reflections leads to a position of approximately $b/4$ for the molecular centre. With an origin chosen on the two-fold screw axis parallel to c the co-ordinates of the four molecular centres in the unit cell then become $a/8, b/4, 0$; $-a/8, -b/4, c/2$; $3a/8, 3b/4, c/2$; $5a/8, b/4, 0$. These positions are also found to lead to a reasonable system of molecular packing.

The trial model used in these preliminary tests consisted of two fused regular planar hexagons containing identical atoms (carbon) with bond lengths of 1·40 Å. Structure factors were calculated for various orientations of this model, and the best agreements were obtained when the long axis (L) of the molecule was inclined at about 45° to a in (010), and the plane normal inclined at about 26° to b. At this stage the average discrepancy was about 22% for 50 observed (*h*0*l*) structure factors. Fourier synthesis now gave excellent resolution of all the atoms in the (010) projection (Fig. 3 is the final result), but owing to the assumed centrosymmetry in the model the phase constants were restricted, and detailed refinement could not proceed on this basis. For the next step it is necessary to establish an asymmetric model.

A difficulty is encountered when we try to insert the nitrogen atoms in our model. The four ways consistent with the chemical structure in which this can be done are shown in Fig. 1, and, although chemically identical, each of these arrangements will lead to a different crystal structure when it is adopted as the asymmetric unit, for which only

FIG. 1.

● Nitrogen.

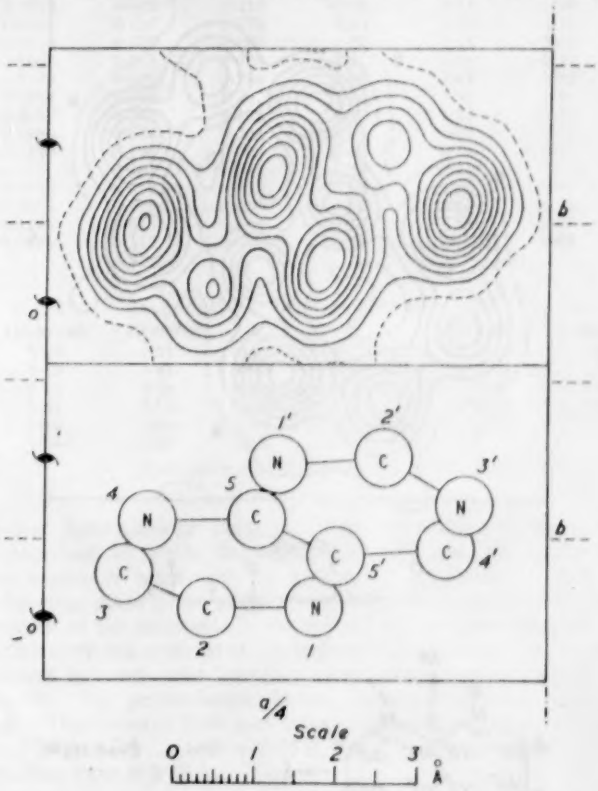
approximate positions of the hexagons have so far been established. In the case of the (010) projection, structures A and B are identical, and so are C and D, for the special position ($a/8$, 0) found for the model; but in the (001) projection all these structures can be distinguished.

In the (010) Fourier synthesis based on the symmetrical trial model it was found that the atoms 1 and 1′ (Fig. 1) had the highest electron-density peak values (6·2 e.Å^{-2}) and atoms 2 and 2′ the lowest (4·8 e.Å^{-2}); all the other symmetrical pairs had almost identical peak densities of about 5·4 e.Å^{-2}. This is fairly strong direct evidence that atoms 1 and 1′ are nitrogen, and 2 and 2′ are carbon, corresponding to structure A or B.

This result was now confirmed by evaluating the (001) projection from the same symmetrical trial model. (Fig. 2 gives the final result.) The screw axes are here equivalent to centres of symmetry and so the phase constants are restricted to 0 or π. In this case, however, the resolution is poor, and only the atoms 2 and 2′ can be clearly resolved. But the result of this Fourier synthesis showed that these two atoms had the same peak density, and this again excludes structures C and D. This result was followed up by evaluating successive Fourier difference syntheses for the projection, based on the four possible structures and taking into account the resulting hydrogen positions. This calculation proved to be conclusively in favour of structure A, the discrepancy figure for the 33 largest structure factors in this zone being reduced to 9·4%. The observations were later extended, by means of very long exposures, to 49 structure factors, and the final discrepancy figure was 12·2%.

Structure A being well established in this way, it was now used as an asymmetric model for intensive refinement of the more important (010) projection. This was carried out by conducting two Fourier syntheses at each stage, one containing the observed structure factors (F_o) as coefficients, and the other the previously calculated structure factors (F_c), the phase angles being the same for both syntheses. This procedure allows for simultaneous refinement of the structure and correction for termination of series errors by means of Booth's " back shift " rule.[13] The projection being non-centrosymmetrical, the parameter shifts at each Fourier stage (after the application of termination of series

FIG. 2. *Electron-density projection on* (001), *showing one molecule. Contour interval,* 1 e.Å^{-2}, *the one-electron line being broken. The molecule is steeply inclined (about* 63°) *to this projection plane.*

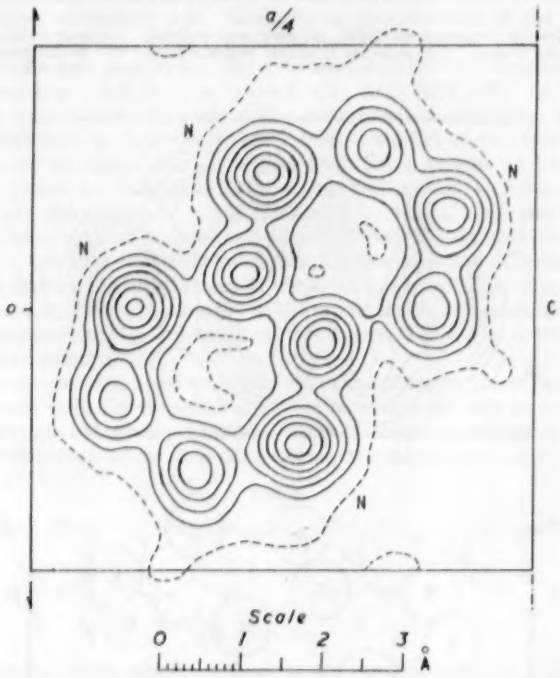


corrections) may be increased beyond the indicated value in order to obtain more rapid convergence to the true structure. For purely asymmetric syntheses a double-shift rule has been suggested,[14] in which the indicated parameter shifts should be doubled at each step to obtain the best possible values. In practice, however, axial reflections with restricted phase constants are generally present, and Shoemaker *et al.*[15] have shown that a 1·7 or 1·6 shift rule may sometimes be best. In this analysis we have used a 1·5 shift rule, which is perhaps slightly on the safe side. After a few cycles, however, the discrepancy in the (*h*0*l*) structure factors was finally reduced to 9·1%.

[13] Booth, *Proc. Roy. Soc.*, **1946**, *A*, **188**, 77.
[14] Donohue, *J. Amer. Chem. Soc.*, 1950, **72**, 949; Cruickshank, *Acta Cryst.*, 1950, **3**, 10.
[15] Shoemaker, Donohue, Schomaker, and Corey, *J. Amer. Chem. Soc.*, 1950, **72**, 2328.

The final electron-density projection, incorporating the 50 observed structure factors, shows good resolution of all the ring atoms (Fig. 3). Three of the four hydrogen atoms appear as bulges on the one-electron contour line. The peak heights also confirm that the nitrogen atoms occupy positions 1, 4, 1′, and 3′.

FIG. 3. *Electron-density projection on* (010). *Contour scale as in Fig. 2. The molecule is inclined at about 27° to this projection plane.*



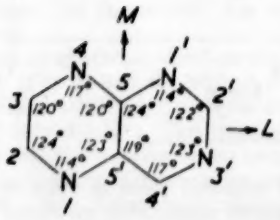


FIG. 4. *Bond angles.*

Co-ordinates and Molecular Dimensions.—The co-ordinates of the ring atoms were determined independently from the projections shown in Figs. 2 and 3, and the mean value is given in Table 1. The hydrogen co-ordinates were calculated on the assumption that they are situated radially at a distance of 1·09 Å from the carbon atoms. The atoms are numbered as indicated in Fig. 4 and the origin is taken on the two-fold screw axis.

The mean plane of the molecule was found by a least-squares method to have the equation :

$$X + 11{\cdot}92Y - 6{\cdot}08Z - 14{\cdot}70 = 0$$

The displacements of the ring atoms from this mean plane are given in the last column of Table 1.

The observed bond lengths are given in Table 2, and compared with values calculated by a molecular-orbital method based on the assumption of a strictly planar structure.[16] The observed valency angles are shown in Fig. 4.

TABLE 1. *Co-ordinates.*

Atom	x	y	z	X (Å)	Y (Å)	Z (Å)	Distance from mean plane of molecule (Å)
N(1)	0·1344	0·034	−0·258	3·32	0·13	−1·63	0·01
C(2)	0·0810	0·029	−0·310	2·00	0·11	−1·96	0·04
C(3)	0·0397	0·137	−0·176	0·98	0·52	−1·11	−0·06
N(4)	0·0510	0·306	0·002	1·26	1·16	0·01	0·02
C(5)	0·1057	0·311	0·066	2·61	1·18	0·42	−0·04
N(1′)	0·1158	0·483	0·258	2·86	1·83	1·63	0·00
C(2′)	0·1684	0·507	0·307	4·16	1·92	1·94	0·04
N(3′)	0·2089	0·356	0·182	5·16	1·35	1·15	−0·03
C(4′)	0·1996	0·216	0·002	4·93	0·82	0·01	0·00
C(5′)	0·1449	0·195	−0·065	3·58	0·74	−0·41	0·01
Mol. centre	0·1251	0·259	0·001	3·09	0·98	0·005	—
H(2)	0·0713	−0·079	−0·457	1·76	−0·30	−2·89	—
H(3)	−0·0012	0·116	−0·220	−0·03	0·44	−1·39	—
H(2′)	0·1777	0·628	0·452	4·39	2·38	2·86	—
H(4′)	0·2324	0·113	−0·098	5·74	0·43	−0·62	—

TABLE 2. *Bond lengths* (Å).

	Observed	Calculated	Δ		Observed	Calculated	Δ
N(1)–C(2)	1·36	1·31	0·05	C(2′)–N(3′)	1·40	1·34	0·06
C(2)–C(3)	1·39	1·41	0·02	N(3′)–C(4′)	1·28	1·31	0·03
C(3)–N(4)	1·32	1·31	0·01	C(4′)–C(5′)	1·42	1·425	0·005
N(4)–C(5)	1·41	1·35	0·06	C(5′)–N(1)	1·39	1·35	0·04
C(5)–N(1′)	1·40	1·35	0·05	C(5′)–C(5)	1·35	1·435	0·085
N(1′)–C(2′)	1·34	1·31	0·03				

Root mean square discrepancy, 0·047.

Orientation and Intermolecular Distances.—The orientation of the molecule in the crystal can be expressed by giving the angles *LOa*, *LOb*, etc., which the molecular axes L, M, and their normal N make with the a, b, and c crystal axes. Axes L and M are taken to lie in the mean plane of the molecule and are directed as shown in Fig. 4.

The arrangement of the molecules in the crystal will be clear from the projections in Figs. 5 and 6 which show the contents of the unit cell in relation to the symmetry elements. Some of the closest intermolecular contacts occur between molecules separated by a b translation (Fig. 5). The perpendicular distance between the mean molecular planes is here only 3·36 Å. The atoms in these molecules which overlie each other most closely are N(4) . . . C(3) = 3·36 Å, N(1′) . . . C(5) = 3·37 Å, C(2′) . . . C(4′) = 3·40 Å, C(5′) . . . N(1) = 3·42 Å, and four other pairs at 3·46 Å.

TABLE 3. *Orientation.*

LOa = 46·9°	*MOa* = 135·6°	*NOa* = 85·7°
LOb = 73·3°	*MOb* = 68·6°	*NOb* = 27·3°
LOc = 47·9°	*MOc* = 53·3°	*NOc* = 117·0°

Between the reference molecule (x, y, z) and the one derived from it by the operation of the two-fold screw axis ($\bar{x}$, $\bar{y}$, $\frac{1}{2} + z$) there is one very close approach, N(4) . . . C(3) = 3·46 Å. Between the reference molecule and the one derived by the operation of the n glide plane ($\frac{1}{2} - x$, $\frac{1}{2} + y$, $\frac{1}{2} + z$) there occurs another very close approach, N(3′) . . . C(4′) = 3·33 Å. Between molecules separated by a c translation (Fig. 6) there are two very

[16] Goodwin and Porte, following paper.

close contacts, N(1′) . . . C(2) = 3·34 Å, and C(2′) . . . N(1) = 3·39 Å. All other intermolecular distances are greater than about 3·5 Å.

Accuracy.—Standard deviations for the atomic co-ordinates were estimated by Cruickshank's method.[17] The results obtained have been increased by a factor of 2 to allow for the non-centred projection, and allowance has also been made for the comparatively small number of F values available in relation to the number of unknown parameters. The y co-ordinates were obtained from a largely unresolved projection for which Cruickshank's treatment is not strictly applicable, and the standard deviations in this case have been increased by a further 25%.

FIG. 5. *Projection on* (001) *showing minimum intermolecular contacts.*

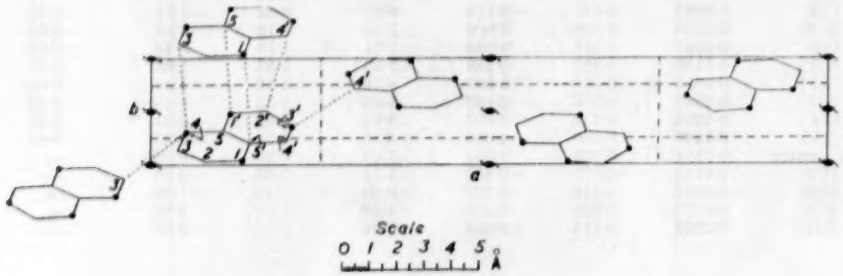
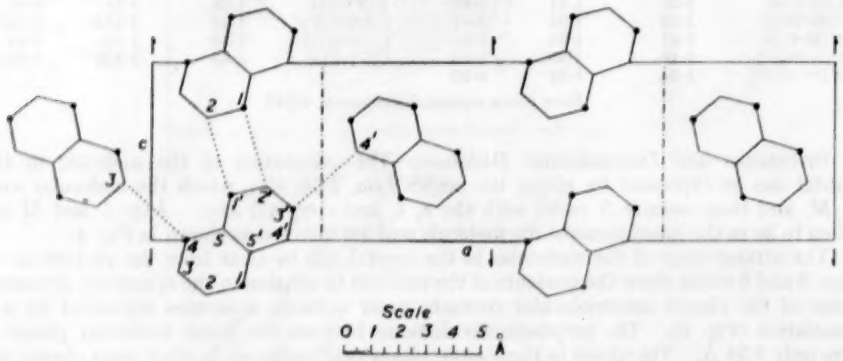


FIG. 6. *Projection on* (010) *showing minimum intermolecular contacts.*



After allowance for all these factors we obtain the following values :

Carbon	.....	$\sigma(x) = 0{\cdot}022$ Å; $\sigma(y) = 0{\cdot}03$ Å; $\sigma(z) = 0{\cdot}023$ Å.
Nitrogen	.....	$\sigma(x) = 0{\cdot}018$ Å; $\sigma(y) = 0{\cdot}025$ Å; $\sigma(z) = 0{\cdot}019$ Å.

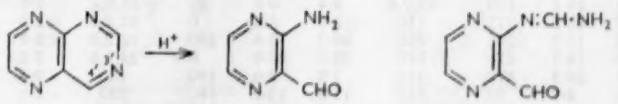
The standard deviation of a C–C bond is 0·035 Å and of a C–N bond 0·033 Å. The standard deviation of a bond angle is about 2·3°, and the standard deviation of electron density is 0·27 e.Å^{-2} for the (001) projection and 0·42 e.Å^{-2} for the (010) projection.

Discussion.—One of the most important questions involved in this analysis is whether the pteridine molecule is strictly coplanar. It is certainly nearly so, and the small deviations found are given in Table 1. The mean displacement of 0·03 Å is certainly not significant. The maximum displacement of a carbon atom is 0·06 Å, and this is measured

[17] Cruickshank, *Acta Cryst.*, 1949, **2**, 65, 154; 1950, **3**, 72; Cruickshank and A. P. Robertson, *ibid.*, 1953, **6**, 698.

almost entirely by the *y* co-ordinate. In the usual notation we have $t = \delta l/\sigma = 2{\cdot}00$. The *y* co-ordinates were determined from 49 independent structure factors, resulting in 29 degrees of freedom. For $P = 0{\cdot}05$ the value of t for such a distribution is 2·045. The displacement of this atom is therefore not significant, or at most is of possible significance only. The maximum displacement of a nitrogen atom is 0·03 Å, for which $t = 1{\cdot}20$, and this is not significant. It may therefore be said that the pteridine molecule is planar to within the limits of experimental error. Owing to the non-centrosymmetric structure, and especially because of the comparatively small number of observed reflections, these limits are unfortunately rather wide. Deviations of up to 0·06 Å from a planar structure cannot be excluded.

The bond lengths observed in pteridine are given in Table 2, together with certain molecular-orbital calculations for this structure. Again owing to the rather large uncertainties in our observed lengths, it would not be profitable to discuss these figures in detail at the present stage. The mean discrepancy between observed and calculated lengths is within the limits of experimental error. It is of interest, however, that the largest discrepancy occurs in the case of the central bond, C(5′)–C(5), where the observed value is much too low. In the naphthalene structure [18] where much more accurate data are available, a similar, though smaller, discrepancy is found. In both molecules it appears that the symmetrical Kekulé structure should be given more weight in the calculations, but any theoretical justification for this is hard to find. Much the shortest observed bond length in pteridine is N(3′)–C(4′) = 1·28 Å. Nucleophilic substitution is known to take place at atom 4′. On treatment with acid pteridine is converted into 2-aminopyrazine-3-aldehyde, and ring fission probably takes place at this bond. More recently it has been shown [19] that pteridine can be split to form the derivative (II) by treatment with 2N-aqueous sodium carbonate at 20°.



(II)

With regard to the minimum intermolecular-approach distances observed in the crystal structure, it is of interest that the majority of the contacts of less than 3·5 Å, and all those under 3·4 Å, are between a carbon atom of one molecule and a nitrogen atom of another molecule. However, none of these distances (minimum 3·33 Å) is less than the sum of the van der Waals radii of the atoms concerned, and it is not necessary to invoke any form of hydrogen bond.

Experimental

It was not possible to obtain satisfactory single crystals of pteridine from any of the usual solvents owing to its extreme solubility. By vacuum-sublimation fine plates were obtained, developed on (100), but the maximum thickness of these was only about 0·02 mm. Rotation, oscillation, and moving-film photographs were taken about each of the crystallographic axes with copper $K\alpha$ radiation ($\lambda = 1{\cdot}542$ Å). The multiple-film technique [20] was employed on the Weissenberg exposures, and the intensities were estimated visually. For the (*hk*0) and (*h*0*l*) zones the crystals employed had cross sections perpendicular to the rotation axes of 0·50 by 0·02 mm., and approximate absorption corrections were worked out graphically. The correction factor varied from 1·02 to 1·31. For the (0*kl*) zone the crystal cross section was 0·70 by 0·60 mm. and absorption corrections were neglected. In this zone only 9 out of a possible 18 reflections could be recorded.

The mosaic crystal formula was assumed, and the resulting structure factors (F_o) are given in Table 4.

[18] Abrahams, Robertson, and White, *Acta. Cryst.*, 1949, **2**, 233, 238; Ahmed and Cruickshank, *ibid.*, 1952, **5**, 852.
[19] Albert, Brown, and Wood, *J.*, 1956, 2066.
[20] Robertson, *J. Sci. Instr.*, 1943, **20**, 175.

TABLE 4. *Measured and calculated structure factors and phase angles (α).*

hkl	F_o	F_c	α°	*hkl*	F_o	F_c	α°	*hkl*	F_o	F_c	α°
000	—	272·0	—	20,0,2	13·4	13·3	2	15,1,0	9·6	11·8	0
200	<0·6	0·2	180	22,0,2	3·7	3·5	282	16,1,0	<2·1	1·7	180
400	73·5	63·1	180	24,0,2	7·3	7·9	179	17,1,0	15·3	14·2	180
600	<1·1	0·0	—	203	24·3	25·1	87	18,1,0	16·2	14·8	0
800	11·7	11·2	180	403	15·4	13·8	157	19,1,0	14·3	15·0	180
10,0,0	<1·6	0·3	0	603	6·7	6·9	285	20,1,0	<2·5	0·1	0
12,0,0	41·0	37·7	180	803	4·7	4·7	38	21,1,0	5·7	8·7	0
14,0,0	<2·0	3·1	0	10,0,3	14·4	14·3	273	22,1,0	4·8	4·7	180
16,0,0	<2·3	1·1	180	204	10·2	9·9	82	23,1,0	3·0	3·6	0
18,0,0	<2·5	1·1	0	404	11·8	11·0	183	30,1,0	2·1	2·7	180
20,0,0	9·0	7·9	0	604	<3·3	2·7	84	120	<1·8	1·4	0
22,0,0	<3·8	0·9	180	804	<3·4	1·7	40	220	<1·8	0·6	0
24,0,0	4·9	6·2	0	10,0,4	<3·5	1·9	242	320	6·1	3·9	180
020	<1·8	5·2	0	12,0,4	9·4	10·3	175	420	19·0	21·0	180
040	<2·3	4·2	0	14,0,4	16·6	16·7	272	520	8·4	7·7	0
002	27·2	25·1	180	16,0,4	6·7	6·8	3	620	3·0	0·1	0
004	29·4	26·2	357	18,0,4	7·9	8·0	86	720	7·1	6·9	180
006	<3·8	3·4	14	205	5·8	3·5	262	820	12·7	12·7	0
011	64·2	75·4	87	405	10·9	10·3	181	920	11·3	11·5	180
013	13·0	10·5	93	605	14·3	16·3	92	10,2,0	4·1	0·0	—
015	8·7	7·7	91	805	6·0	5·4	356	11,2,0	7·5	7·4	0
022	36·4	40·8	181	10,0,5	<3·9	4·9	90	12,2,0	9·0	10·2	0
024	4·8	3·1	13	12,0,5	9·9	8·2	181	13,2,0	<2·3	1·8	180
031	5·9	7·1	296	14,0,5	7·6	8·6	271	14,2,0	<2·3	0·3	180
033	9·0	5·9	256	16,0,5	7·8	7·7	5	15,2,0	2·7	2·9	180
201	44·9	53·9	93	18,0,5	3·5	4·6	270	16,2,0	2·8	3·3	0
401	41·5	45·7	2	206	<3·8	0·7	45	17,2,0	6·1	5·4	180
601	32·5	28·9	96	406	11·4	10·5	3	18,2,0	<2·5	0·3	0
801	27·9	27·7	1	606	6·3	5·0	268	19,2,0	4·1	5·2	0
10,0,1	21·5	20·8	92	806	12·9	12·3	183	20,2,0	9·8	12·0	180
12,0,1	24·1	24·1	186	10,0,6	4·4	3·8	93	21,2,0	7·3	6·2	0
14,0,1	19·2	18·3	277	110	<3·0	8·4	0	22,2,0	<2·3	0·0	—
16,0,1	14·5	15·7	355	210	69·9	73·8	180	23,2,0	<2·3	0·0	—
18,0,1	16·6	14·7	276	310	23·3	22·9	0	24,2,0	3·2	4·4	0
20,0,1	18·1	20·3	179	410	1·2	2·0	180	130	<2·3	2·1	0
22,0,1	9·3	8·7	90	510	11·8	12·2	180	230	<2·3	3·4	0
202	4·4	6·4	307	610	28·9	28·3	180	330	<2·3	3·5	0
402	20·9	23·6	356	710	1·4	5·6	0	430	3·0	2·4	180
602	27·7	28·8	263	810	1·8	3·2	0	530	3·5	4·1	180
802	24·0	23·8	188	910	12·7	9·2	180	630	3·0	2·1	0
10,0,2	27·2	27·9	102	10,1,0	20·1	18·3	180	730	6·0	8·9	180
12,0,2	<2·9	1·9	286	11,1,0	10·3	11·0	180	830	3·9	1·0	0
14,0,2	6·6	7·2	104	12,1,0	<1·8	2·8	0	930	3·2	3·4	0
16,0,2	<3·4	0·8	21	13,1,0	15·0	15·1	0	22,3,0	2·5	3·3	0
18,0,2	<3·6	1·1	326	14,1,0	18·1	16·2	0				

The various Fourier syntheses were effected by the usual numerical methods. The structure factors and phase constants were finally recalculated from the latest atomic positions (Table 1) and are given in Table 4 under F_c and α. In these calculations the f curves of McWeeny [21] were used for carbon, nitrogen, and hydrogen, with a temperature factor of $B = 4{\cdot}8 \times 10^{-16}$, which was derived from a comparison of observed and calculated structure factors. The final discrepancies, expressed as $\sum|F_o - F_c|/\sum F_o$, were 9·1% for the (*h*0*l*) zone, 12·2% for the (*hk*0) zone, and 11·1% overall.

We thank Professor Adrien Albert for providing the pteridine used, and the Gourock Ropework Company for a Studentship which enabled one of us (T. A. H.) to take part in the work.

CHEMISTRY DEPARTMENT, UNIVERSITY OF GLASGOW. [*Received, March 29th*, 1956.]

[21] McWeeny, *Acta Cryst.*, 1951, **4**, 513.

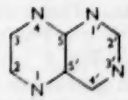
693. *Calculated Bond Lengths in Some Cyclic Compounds. Part IV.* Pteridine and Melamine, and a Correlation Curve for C–N Bonds.*

By T. H. Goodwin and A. L. Porte.

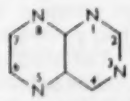
Energy levels, π-electron distributions, and mobile bond orders have been deduced for pteridine and melamine. The results for melamine have been used with those for other compounds, the crystal structures of which have been accurately determined, to establish a curve correlating π-bond order and bond length for C–N bonds in conjugated systems of six-membered rings. This has then been applied to the bond orders obtained for pteridine to permit comparison of the interatomic distances thus expected with those measured by Hamor and Robertson.[1]

Hamor and Robertson [1] have recently investigated the interatomic distances in pteridine, their values having a standard deviation of about 0·03 Å. The work reported in this paper began as an attempt to predict the bond lengths in this substance by the method of molecular orbitals, but prediction became more difficult as the uncertainties in the curve correlating bond order and bond length were realised. We have therefore developed a new correlation curve and from it have derived bond lengths for comparison with those measured.

Calculations on Pteridine.—In pteridine (I), the atoms of which are here numbered as in the foregoing paper, each of the six carbon and four nitrogen atoms contributes one p_z electron to the π-molecular-orbital system, the secular equations for which were set up in



(I) Numbering used in this paper.



(I) Usual chemical numbering.

the usual way, the Coulomb integral of carbon being written α and that of nitrogen $\alpha + \frac{1}{2}\beta$. The resonance integrals for C–C and C–N were, as usual, taken to be equal, *viz.*, β, and the overlap integrals were neglected. It was assumed that the molecule is planar although, as the discussion given by Hamor and Robertson [1] suggests, it seems just possible that this is not quite correct. We had completed the first section of the calculations on pteridine before the *X*-ray results were available, though not before the possibility had been mooted by Albert.[2] We believed, however, that the molecule would be shown by the *X*-ray work to be flat.

Table 1. *π-Electron molecular-orbital energy levels (E_i) in pteridine in order of increasing energy.*

i	E_i	i	E_i	i	E_i	i	E_i
1	$\alpha + 2{\cdot}48377\beta$	4	$\alpha + 1{\cdot}10302\beta$	7	$\alpha - 0{\cdot}90997\beta$	9	$\alpha - 1{\cdot}45460\beta$
2	$\alpha + 1{\cdot}84220\beta$	5	$\alpha + 0{\cdot}91874\beta$	8	$\alpha - 1{\cdot}07655\beta$	10	$\alpha - 2{\cdot}15775\beta$
3	$\alpha + 1{\cdot}58342\beta$	6	$\alpha - 0{\cdot}33221\beta$				

Table 2. *π-Electron distribution (q_r) in the ground state of pteridine.*

r	1	2	3	4	5	1′	2′	3′	4′	5′
q_r	1·126	0·905	0·872	1·166	0·891	1·224	0·829	1·194	0·831	0·962

The determination of the energy levels E_i was carried out as described in Part I [3] of this series and Table 1 gives their values. By using each of these energy levels in turn the

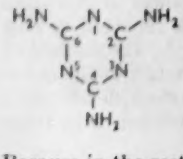
* Part III, *J.*, 1955, 4451.

[1] Hamor and Robertson, preceding paper.
[2] Albert, *Quart. Rev.*, 1952, **6**, 197.
[3] Goodwin and Vand, *J.*, 1955, 1683.

π-electron distribution q_r and the π-bond orders p_{rs} were calculated. They are given in Tables 2, 5, and 6.

To convert the bond orders into bond lengths a correlation curve is necessary. For the C–C bonds this has already been established in Part I [3] but for the C–N bonds the position is much less satisfactory. In Parts I and II [4] the linear correlation curve given by Cox and Jeffrey [5] was used. As the flavanthrone considered in those papers contains only two C–N bonds out of the twenty bonds in the asymmetric unit of the molecule it seemed unnecessary to seek a more accurate correlation. In pteridine eight of the eleven bonds are between carbon and nitrogen atoms. Further, Davies [6] has pointed out that the melamine bond orders used to establish Cox and Jeffrey's curve are at fault. We have therefore recalculated them.

Calculations on Melamine.—In melamine, 2 : 4 : 6-triamino-*s*-triazine (II), each of the ring carbon and nitrogen atoms contributes one p_z electron to the molecular-orbital system but each of the amino-nitrogen atoms contributes two. Thus nine molecular orbitals accommodate twelve electrons.



(II)

The molecule has D_{3h} symmetry and examination of the character table shows that the π-electron energy levels must be $3E'' + 3A_2''$, the E'' being doubly degenerate. In evaluating them the Coulomb integral for the ring nitrogen atoms was again set at $\alpha + \frac{1}{2}\beta$ but that for the amino-nitrogen atoms at $\alpha + \beta$. Because in the rest of this paper inductive effects of the nitrogen atoms on the Coulomb integrals of carbon atoms have been neglected we did not at first include them for melamine, but at the suggestion of a Referee we have done so. The results are included under the primed symbols E'_i, q'_r, p'_{rs}. Table 3 gives the energy levels for melamine, the first six being (doubly) occupied in the ground state. The π-electron distribution is then found to be: carbon $q = 0{\cdot}800$, $q' = 0{\cdot}827$; ring N $q = 1{\cdot}430$, $q' = 1{\cdot}417$; amino-N $q = 1{\cdot}770$, $q' = 1{\cdot}754$. The bond orders are ring $p = 0{\cdot}563$, $p' = 0{\cdot}571$; side-chain C–N $p = 0{\cdot}520$, $p' = 0{\cdot}521$. The inductive effects of the nitrogen atoms thus make only a small change in the charge distribution and practically no change in the bond orders.

TABLE 3. *π-Electron molecular-orbital energy levels (E_i) for melamine in order of increasing energy.*

i	Symmetry	$E_i - \alpha$	$E_i' - \alpha$	i	Symmetry	$E_i - \alpha$	$E_i' - \alpha$
1	A_2''	$2{\cdot}5697\beta$	$2{\cdot}6800\beta$	5, 6	E''	$0{\cdot}7274\beta$	$0{\cdot}7349\beta$
2, 3	E''	$1{\cdot}8733\beta$	$1{\cdot}9666\beta$	7, 8	E''	$-1{\cdot}1007\beta$	$-0{\cdot}9514\beta$
4	A''	$0{\cdot}8924\beta$	$0{\cdot}8946\beta$	9	A''	$-1{\cdot}9622\beta$	$-1{\cdot}8247\beta$

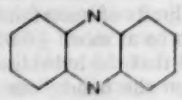
The C–N *Correlation Curve.*—Our bond orders for melamine are quite different from those given by Cox and Jeffrey who regarded the nine C–N bonds as equivalent and deduced a value of 0·658 for p. Their conclusion about the equivalence of the bonds was based on the *X*-ray results of Hughes [7] who, estimating that his measurements were not in error by more than 0·05 Å, gave lengths for the ring bonds which averaged 1·343 Å, and for the extracyclic C–N linkages which averaged 1·353 Å.

In comparing these with the calculated bond orders it is desirable to make a small correction for the effect on the bond lengths of the net charges on the atoms. When reasonable values of the dielectric constant and the force constants in the bonds are taken, a contraction of 0·007 Å in the ring bonds and a stretching of 0·004 Å in the side linkages are deduced; thus the measured lengths must be increased and decreased respectively by these amounts in order to obtain the lengths appropriate to bonds between neutral atoms. If this is done the lengths of the bonds become 1·350 (ring) and 1·349 (extracyclic C–N) though to apply corrections of 0·007 Å and 0·004 Å when the experimental uncertainty is reported as 0·05 Å seems rather naïve. We are forced, therefore, to ignore these

[4] Goodwin, *J.*, 1955, 1689.
[5] Cox and Jeffrey, *Proc. Roy. Soc.*, 1951, *A*, **207**, 110.
[6] Davies, *Trans. Faraday Soc.*, 1955, **51**, 449.
[7] Hughes, *J. Amer. Chem. Soc.*, 1941, **63**, 1737.

corrections, recognising that the points for melamine are still not as reliable as we should like.

There is, however, a number of other compounds containing accurately measured C–N linkages. These, and the results for them, are listed in Table 4. Only for *s*-triazine is the



(III)

(IV)

charge correction to the bond length as great as 0·003 Å; it has therefore been neglected in all cases.

The extremities of the single bond–double bond range are not very satisfactory. Cox and Jeffrey give, for the pure single bond a length of 1·475 Å, but in all the compounds they quote the hybridisation as sp^3 whereas sp^2 hybridisation is involved in the condensed-ring

TABLE 4. *Mobile orders and lengths of some* C–N *bonds.*

Compound	α_N	p_{C-N}	Bond lengths	Method of measurement
Melamine (II)	See text	0·563 *	1·343 ± 0·05	*X*-Ray [3]
		0·520 *	1·353 ± 0·05	
s-Triazine	$\alpha + 0{\cdot}5\beta$	0·654 * [6]	1·319 ± 0·005	*X*-Ray *
α-Phenazine (III)	$\alpha + 0{\cdot}6\beta$	0·603 †	1·345 ± 0·009	*X*-Ray [5, c]
Pyrimidine (IV)	$\alpha + 0{\cdot}6\beta$	0·656 [14]	1·33	*X*-Ray ‡
Pyridine	$\alpha + 0{\cdot}5\beta$	0·654	1·340	Micro-wave [d]

* This paper or unpublished work of present authors.
† Personal communication by Pullman quoted in ref. *c*.
‡ Predicted by Clews and Cochran (*Acta Cryst.*, 1948, **1**, 4) on the basis of their and other data (Pitt, *ibid.*, p. 168; cf. Clews and Cochran, *ibid.*, 1949, **2**, 46).
[3] Wheatley, *Acta Cryst.*, 1955, **8**, 224. [5] Herbstein and Schmidt, *ibid.*, p. 399. [c] *Idem*, *ibid.*, p. 406. [d] Bak, Hansen, and Rastrup-Andersen, *Acta Chem. Scand.*, 1955, **9**, 1355.

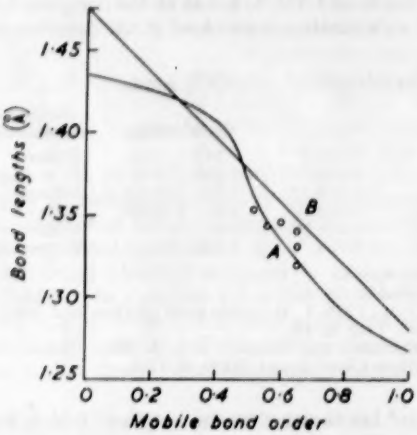
compounds considered here. Since Coulson [8] has shown that the length of 1·54 Å for the tetrahedral C–C becomes 1·50 Å in the trigonal hybrid we suggest that a similar shortening is to be expected in C–N although the data for its calculation are not available. We have therefore taken 1·435 Å for the sp^2 C–N bond of order zero.

For the pure bond of π-order 1, Cox and Jeffrey select 1·28, and the covalent radii values of Stevenson and Schomaker,[9] with the electro-negativity correction according to Gordy,[10] give 1·27 Å. We have adopted another method to determine this value. Of the six intermediate points listed above, five are fairly self-consistent but that for pyridine stands apart. Any reasonable order–length curve among the rest must pass through or very near (0·600, 1·336). We have therefore taken this point as a datum for developing our order–length curve. In the C–C correlation curve established in Part I (Fig. 1, *J.*, 1955, 1687) the ordinates corresponding to orders 0 and 0·6 are 1·50 and 1·406 Å. We have therefore displaced and proportionally compressed the C–C curve so that it passes through (0, 1·435) and (0·600, 1·336). The curve shown results and passes through the points (0·1, 1·431), (0·2, 1·425), (0·3, 1·418), (0·4, 1·407), (0·5, 1·375), (0·6, 1·336), (0·7, 1·312), (0·8, 1·291), (0·9, 1·277), and (1·0, 1·267). The last of these gives the length of the pure double bond and agrees closely with the values deduced from the results of Stevenson and Schomaker and of Gordy. The justification for this procedure is first that since the range of C–N bond orders likely to be met is from 0·5 to 0·7 it is this part of the curve which is the most important. Over this range, and within the limits of accuracy of the calculations and measurements the curve drawn is a perfectly reasonable one. Secondly, the C–C curve of Part I has given quite reliable information in all cases to which it has been applied

[8] Coulson, Victor Henri Memorial Volume, "Contribution à l'étude de la structure moléculaire," Desoer, Liège, 1948, p. 15.
[9] Stevenson and Schomaker, *J. Amer. Chem. Soc.*, 1941, **63**, 37.
[10] Gordy, *J. Chem. Phys.*, 1947, **15**, 81.

and it is reasonable to suppose that a curve of similar shape will be required for C–N bonds. The difference between our curve and that of Cox and Jeffrey over the technically important range is due chiefly to the more accurately calculated bond orders which we have used.

Two further points remain to be noted. The first is that, bearing in mind the estimated experimental errors in the interatomic distances and the uncertainty as to their significance in some cases, it is difficult to decide on the limits of uncertainty to be attached to lengths read off from our curve, but we believe it to be at most ±0·02 Å, and perhaps less. The second is that, although Coulson [8] points out that the hybridisation ratio and therefore the atomic radius depends on the angle between the bonds, our calculations (which will be described elsewhere) show that in the compounds which we have been discussing here the correction necessary is only +0·005 Å (in the atomic *radius*) if the valency angle is 114°, and −0·002 Å if it is 124°. Since the angles at the ends of any C–N bond tend to be one



Order–length curve for C–N bonds.
A, This paper. *B*, Cox and Jeffrey.[5]

smaller and one larger than 120° the corrections tend to offset each other (although they are not proportional to the angle), giving total corrections of only about 0·002 Å (usually positive). These are clearly not significant. Although we have usually quoted derived bond lengths to three places of decimals we do not believe that they can be relied on to the third figure; they are given in this form to facilitate their use in later work.

TABLE 5. *π-Bond orders with derived and observed bond lengths for* C–C *bonds in pteridine.*

		Bond length		
r–*s*	p_{rs}	der.	obs.	Δ
2–3	0·590	1·410	1·39	−0·02
5–5′	0·519	1·435	1·35	−0·09
4′–5′	0·549	1·425	1·42	−0·01

TABLE 6. *π-Bond orders* (p_{rs}) *with derived and observed bond lengths for* C–N *bonds in pteridine.*

		Bond length					Bond length		
r–*s*	p_{rs}	der.	obs.	Δ	*r*–*s*	p_{rs}	der.	obs.	Δ
1–2	0·722	1·307	1·36	0·05	5–1′	0·558	1·349	1·40	0·05
1–5′	0·552	1·351	1·39	0·04	1′–2′	0·709	1·310	1·34	0·03
3–4	0·715	1·309	1·32	0·01	2′–3′	0·599	1·337	1·40	0·06
4–5	0·551	1·352	1·41	0·06	3′–4′	0·706	1·311	1·28	−0·03

Bond Lengths in Pteridine.—Tables 5 and 6 include the calculated and the measured interatomic distances in pteridine; in both tables Δ signifies measured length *minus* derived length.

Considering the information in Table 5 first, the agreement for bonds 2–3 and 4′–5′ is excellent, but that for 5–5′ is very poor. This C–C bond has a measured length which is almost that of a pure double link, a value which is, according to molecular-orbital theory, impossible for this type of system. In addition the greater electronegativity of the nitrogen atoms must cause them to draw electrons towards themselves and away from the C–C bonds which should, therefore, all be longer than in naphthalene. This is, of course, reflected in our calculations and in the measurements on bonds 2–3 and 4′–5′. Hamor and Robertson agree that this value of 1·35 Å for the central linkage is too short but point out that a similar, though smaller discrepancy is found in naphthalene (obs.[11] 1·395 Å; calc. 1·424 Å, as quoted by Coulson, Robertson, and Daudel; [12] 1·435 Å from the curve of Part I). The corresponding bridge bonds in anthracene, on the other hand,[13] measure 1·440, within experimental error of the calculated value of 1·430 Å (1·450 from the curve of Part I).

For the results in Table 6, $|\Delta|_{mean} = 0{\cdot}04$. The derived lengths are almost always greater than the observed, but as Hamor and Robertson point out, their standard deviation of bond length is 0·03 Å, so that the mean discrepancy is within the limits of experimental error. It is of interest, however, that, if the atoms 5 and 5′ are equally displaced along the line joining them so that they become separated by the distance 1·435 Å indicated by our calculations, then the discrepancies in the bonds C_5–N_4, C_5–$N_{1'}$, $C_{5'}$–N_1, $C_{5'}$–$C_{4'}$ are greatly reduced, to 0·04, 0·02, 0·01, and −0·03 Å, respectively.

Again, much the shortest bond measured is 3′–4′ = 1·28 Å, and the fact that nucleophilic substitution takes place at atom 4′ and that this bond breaks on treatment with acid may well be due to the density and distribution of electrons here. These points support the shortness of this linkage [our calculation of the charge distribution throughout the molecule (Table 2) makes $C_{2'}$ and $C_{4'}$ equally deficient in electrons though Chalvet and Sandorfy,[14] by algebraic superposition of results for compounds with a single nitrogen atom in different positions, find $C_{4'}$ the more deficient] but 1·28 is almost, if not quite, the limit for a pure double bond between carbon and nitrogen, again impossible in this type of compound. If this linkage were lengthened to, say, our calculated value by a procedure similar to that indicated for C_5–$C_{5'}$ bonds, then the bonds 4′–5′ and 2′–3′ would again be shortened and agreement with our calculations improved. With two bonds in the structure apparently so very much shorter than expected we postpone further discussion.

The authors gratefully acknowledge many useful discussions with Professor J. M. Robertson, F.R.S., and Mr. T. A. Hamor, B.Sc., during this work.

Chemistry Department, University of Glasgow. [*Received, April 3rd,* 1956.]

[11] Abrahams, Robertson, and White, *Acta Cryst.*, 1949, **2**, 233, 238.
[12] Coulson, Robertson, and Daudel, *Proc. Roy. Soc.*, 1951, *A*, **207**, 306.
[13] Mathieson, Robertson, and Sinclair, *Acta Cryst.*, 1950, **3**, 245, 251.
[14] Chalvet and Sandorfy, *Compt. rend.*, 1949, **228**, 556.

694. peri-*Hydroxycarbonyl Compounds. Part II.** *The Effect of Ring Size on Hydrogen Bonding.*

By V. C. Farmer, N. F. Hayes, and R. H. Thomson.

Hydrogen bonding in *peri*-hydroxy-indanones, -tetralones, and -benzo-*cyclo*heptenones and related compounds has been studied spectroscopically and by reactions with diazomethane and phenyl *iso*cyanate. It is shown that chelation in the five-membered is much weaker than in the six- and seven-membered ring ketones, but there is no sharp distinction between the two larger ring systems.

Two major anomalies are reported : (*a*) quinol ketones of type (I) are not methylated by diazomethane; (*b*) all the *peri*-hydroxylated five-membered ring ketones examined failed to react with phenyl *iso*cyanate.

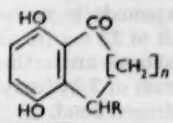
Phenolic hydroxyl groups *ortho* or *peri* to a carbonyl group frequently exhibit abnormal behaviour which is ascribed to intramolecular hydrogen bonding. Failure to react with diazomethane under normal conditions is a well-known example. This is of diagnostic value in establishing the structure of hydroxy-anthraquinones, -flavones, -xanthones, etc., although it is true that such *peri*-hydroxyl groups can sometimes be methylated by prolonged treatment with a large excess of the reagent, *e.g.*, 3 : 7 : 3′ : 4′-tetra-acetylquercetin [1] and mellein.[2] There are also a few cases in which *peri*-hydroxyl groups react normally with diazomethane; these include 3-hydroxyphthalic anhydride,[3] 7-hydroxy-3-methylphthalide,[4] and 4-hydroxycoumaranones.[5] In 4 : 6-dihydroxycoumaranone, the 4-hydroxyl group is preferentially methylated.[6] In all these normal examples the carbonyl group is located in a five-membered ring.

We have now examined a wider range of compounds of this type (see Experimental section) including a number of *peri*-hydroxyindanones which have been compared with the ring-homologous tetralones and benzo*cyclo*heptenones. Some *peri*-hydroxyl derivatives of the latter do not react with diazomethane, *e.g.*, 1′ : 4′-dihydroxy-1 : 2-benzo*cyclo*heptene-3 : 7-dione [7] and 1′-hydroxy-2′ : 3′-dimethoxy-1 : 2-benzo*cyclo*hepten-3-one.[8] 1′ : 2′ : 3′ : 4-Tetrahydroxy-1 : 2-benzo*cyclo*hepten-3-one can be converted into the 1′ : 2′ : 3′-trimethyl ether with some difficulty but it is not possible to methylate the *peri*-hydroxyl group in the case of the 2′ : 3′ : 4-triacetate and the 2′ : 3′ : 4-trimethyl ether.[9] Our findings agree with the earlier work and it is broadly true that a hydroxyl group behaves normally towards diazomethane when *peri* to a carbonyl group in a five-membered ring but is inert if the carbonyl group is part of a six- or seven-membered ring. On the other hand all the hydroxyl groups were readily methylated with methyl sulphate except in the 8-hydroxytetralone group. There is, however, a curious, and as yet inexplicable, exception to the regularities of diazomethane methylations. We find that the 4 : 7-dihydroxyindanones (I; $n = 1$) and the corresponding tetralones and benzo*cyclo*heptenones (I; $n = 2$ and 3 respectively) do not react with diazomethane. Even after prolonged contact, at a low temperature, in various solvents, no methylation occurred. It was noted previously [10] that 5 : 8-dihydroxytetralone was not methylated by diazomethane although some reaction, probably with the carbonyl group, could be effected by prolonged treatment. 2 : 5-Dihydroxyacetophenone is also unaffected by this reagent. The failure of the hydroxyl

* Part I, *J.*, 1956, 1585.

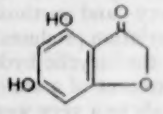
[1] Kubota and Perkin, *J.*, 1925, **127**, 1889.
[2] Blair and Newbold, *J.*, 1955, 2871.
[3] Corbellini and Rossi, *Gazzetta*, 1931, **61**, 281.
[4] Hochstein and Patternack, *J. Amer. Chem. Soc.*, 1951, **73**, 5008; Horii, Okumura, and Tamura, *J. Pharm. Soc. Japan*, 1953, **73**, 526.
[5] Gruber and Hoyos, *Monatsh.*, 1949, **80**, 303; Gruber and Horváth, *ibid.*, 1950, **81**, 819.
[6] Geissman and Hinreiner, *J. Amer. Chem. Soc.*, 1951, **73**, 782.
[7] Bruce, Sorrie, and Thomson, *J.*, 1953, 2403.
[8] Gardner and Horton, *J. Org. Chem.*, 1954, **19**, 213.
[9] Walker, *J. Amer. Chem. Soc.*, 1955, **77**, 6699.
[10] Thomson, *J.*, 1952, 1822.

groups, not involved in intramolecular hydrogen bonding, to react, suggested that intermolecular hydrogen bonds might be the cause but this was discounted when molecular-weight determinations (ebullioscopic) on representative compounds (I; $n = 1$, R = Me; $n = 2$, R = Me; and $n = 3$, R = H) showed that they were not associated in solution.

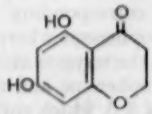


(I)

R = H, Me, or Et



(II)



(III)

Examination of the infrared spectra of these substances revealed no abnormalities. As the compounds concerned are all quinols, an oxidation–reduction could conceivably be responsible for their non-methylation and a few oxidations by diazomethane have been recorded. Arndt and Schlatter [11] found that anthrone and anthranol gave 10 : 10′-dianthronyl when treated with diazomethane in benzene (similar observations were made earlier by Perkin and Storey [12]), and it has been shown that 1 : 4-naphthaquinol [13] and 1 : 4 : 5-trihydroxynaphthalene [14] react with ethereal diazomethane to form naphthaquinonopyrazoles, indicating that the quinols are first oxidised to quinones and subsequently add a molecule of the diazo-compound. However, 2 : 3-dichloronaphthaquinol [15] appears to react normally and we find that quinol itself gives a moderate yield of the dimethyl ether, and that 3 : 6-dihydroxyphthalic anhydride and 3 : 6-dihydroxyphthalimide are methylated smoothly. In any case, when methylation failed, the starting material was usually recovered in high yield so that oxidation alone is not an adequate explanation.

The preferential methylation of the 4-hydroxyl group in 4 : 6-dihydroxycoumaranone (II) was attributed by Geissman and Hinreiner [6] to its greater acidity. The same argument applied to the dihydroxychromanone (III) would imply preferential methylation of the 5-hydroxyl group; as only a monomethyl ether is formed, this must be the 7-methoxy-compound and the difference between the two homologues is evidently due to a stronger hydrogen bond in the chromanone, which is confirmed by the infrared spectra.

Further anomalous behaviour is the failure of almost all the five-membered ring hydroxy-ketones to react with phenyl *iso*cyanate (this includes both hydroxyl groups of II). Phenylurethane formation was attempted by heating the hydroxy-ketone and *iso*cyanate alone, or in a boiling solvent (light petroleum, xylene, anisole) with triethylamine as catalyst, and also in pyridine solution at room temperature.[16] In a single trial, 7-hydroxyindanone did not react with *p*-nitrophenyl *iso*cyanate. The 4 : 7-dihydroxyindanones are again exceptional in forming mono(4)-phenylurethanes. In this respect they are similar to the dihydroxytetralones which form mono(5)-derivatives whereas the dihydroxybenzo*cyclo*heptenones yield bisphenylurethanes. In the latter case, the non-planarity of the seven-membered ring may facilitate the reaction but it is difficult to account for the behaviour of the hydroxyindanones.

Whilst it appears from the foregoing that hydrogen bonding is weakest in the *peri*-hydroxyindanones and strongest in the *peri*-hydroxytetralones, there are many anomalies, and obviously diazomethane and phenyl *iso*cyanate are not reliable reagents for the detection of hydrogen-bonded phenolic groups.

To obtain a better estimate of the degree of hydrogen bonding in the hydroxy-ketones of different ring sizes we then examined their spectroscopic properties. In such compounds, methylation of the hydroxyl group generally results in a shift of the ultraviolet absorption maxima to shorter wavelengths. We find that such shifts are absent (or very small) in

[11] Arndt and Schlatter, *Chem. Ber.*, 1954, **87**, 1336.
[12] Perkin and Storey, *J.*, 1929, 1399.
[13] Moore and Waters, *J.*, 1953, 3405.
[14] Hayes and Thomson, *J.*, 1955, 904.
[15] Bryde and Woodcock, *Ann. Appl. Biol.*, 1953, **40**, 675.
[16] Illari, Marenghi, and Stuani, *Ann. Chim.* (*Italy*), 1953, **43**, 744.

the five-membered ring ketones but are larger in the six- and seven-membered ring compounds. Typical curves are shown in Fig. 1 and the shifts ($\Delta m\mu$) of the long-wavelength maxima are recorded in Table 1. The ultraviolet absorption of the five-membered ring compounds is in line with their chemical properties (anomalies being ignored), indicating no appreciable intramolecular hydrogen bonding. The striking similarity * of the absorption of corresponding hydroxy- and methoxy-compounds is in contrast even to *o*-hydroxyacetophenone where methylation produces a shift of 22 mμ (in alcohol).[17] This indicates that the oxygen atoms in the bicyclic hydroxy-ketones are further apart than in *o*-hydroxyacetophenone and measurement of a scale diagram of 7-hydroxyindanone gives a separation of 3 Å which corresponds to a very weak hydrogen bond.

We have not examined many six- and seven-membered ring compounds as the position here is complicated by steric factors, but at least it is clear that these two groups can be easily distinguished from the five-membered ring compounds. The anomalous 1′-hydroxy-2′ : 3′-dimethoxybenz*oxycloh*eptenone also differs from other members of the same group in that it does not react with phenyl *iso*cyanate. Hydrogen bonding is slightly stronger (see the infrared data), but a steric factor may be important for Gardner and Horton [8]

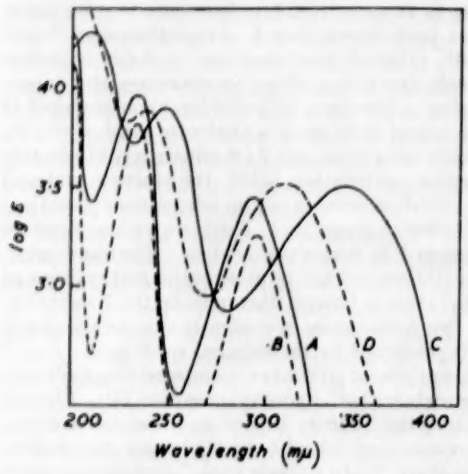


FIG. 1. *A*, 7-*Hydroxyindanone*; *B*, 7-*methoxyindanone*; *C*, 5-*chloro*-8-*hydroxy*-7-*methoxytetralone*; *D*, 5-*chloro*-7 : 8-*dimethoxytetralone* (*in* EtOH).

found that this compound can be obtained from the trimethyl ether with remarkable ease and further work [18] has shown that this occurs when a second methoxyl group is placed next to the one in the *peri*-position. Swain [19] and Harborne [20] have reported that the spectral changes which occur on addition of aluminium chloride or sodium ethoxide to alcoholic solutions of hydroxycarbonyl compounds enable hydrogen-bonded structures to be detected. We investigated this phenomenon briefly but the results were somewhat divergent and did not assist the determination of ring size.

The stretching frequencies of both hydroxyl and carbonyl groups are lowered when these groups form a hydrogen bond, and the displacement from the normal frequencies is a function of the degree of interaction between the groups.[21] Accordingly, these infrared absorption frequencies were determined for the *peri*-hydroxycarbonyl compounds in chloroform solution : the results are summarised in Table 1. The differences between the

* Since this paper was submitted a similar observation has been made by Geissman and Harborne (*J. Amer. Chem. Soc.*, 1956, **78**, 832) in the hydroxyaurone series.

[17] Morton and Stubbs, *J.*, 1940, 1347.
[18] Horton and Spence, *J. Amer. Chem. Soc.*, 1955, **77**, 2894.
[19] Swain, *Nature*, 1953, **172**, 23; *Chem. and Ind.*, 1954, 1480.
[20] Harborne, *ibid.*, p. 1142.
[21] Bellamy, "The Infra-red Spectra of Complex Molecules," Methuen, London, 1954.

carbonyl frequencies of the *peri*-hydroxyl compounds and those of the corresponding *peri*-methoxyl compounds ($\Delta\nu$CO) are also given.

TABLE 1. *Infrared absorption frequencies of the hydroxyl* (νOH) *and carbonyl* (νCO) *vibrations of* peri-*hydroxy-ketones, and the shifts in carbonyl frequency* ($\Delta\nu$CO) *and ultraviolet maximum* ($\Delta m\mu$) *following methylation.*

Compound	νOH (cm.$^{-1}$)	νCO (cm.$^{-1}$)	$\Delta\nu$CO (cm.$^{-1}$)	$\Delta m\mu$
Indanones				
7-Hydroxy	3369	1681	19	0
7-Hydroxy-4-methyl	3369	1678	22	—
7-Hydroxy-3 : 4-dimethyl	3369	1679	22	0
4 : 7-Dihydroxy	3606, 3378	1684	19 †	10
4 : 7-Dihydroxy-3-methyl	3600, 3375	1684	21 †	10
4-Chloro-7-hydroxy-3-methyl	3372	1686	23	0
4-Chloro-7-hydroxy	3371	1686	25	—
Tetralones				
5 : 8-Dihydroxy	3603, B	1643	38 †	30
8-Hydroxy-5-methoxy	B	1644	37	—
8-Hydroxy-5 : 7-dimethoxy-2-methyl	B	1642	46	40
5-Chloro-8-hydroxy-7-methoxy	B	1641	54	30
Benz*cyclo*heptenones				
1′ : 4′-Dihydroxy	3605, B	1637	54 †	45
1′-Hydroxy-2′ : 3′-dimethoxy	B	1616	67	18 *
1′ : 4′-Dihydroxybenz*cyclo*heptene-3 : 7-dione	B	1638	64 †	75
Related Compounds				
4-Hydroxycoumaranone	3455	1697 * 1689	—	0
4 : 6-Dihydroxycoumaranone ‡	—	1679	21 †	0 †
4-Hydroxy-6-methoxycoumaranone ‡	—	1682	18	—
3 : 6-Dihydroxyphthalic anhydride	3520	1762 1833	13 † 14	0
5-Hydroxyflavanone	B	1648	35	19
5-Hydroxy-7-methoxyflavanone	B	1639	33	—
5 : 7-Dihydroxychromanone	3584, B	1643	28 †	—
1 : 2 : 3 : 4-Tetrahydro-5 : 8-dihydroxy-1 : 4-dioxonaphthalene	B	1643	—	—
1 : 2 : 3 : 4-Tetrahydro-5 : 8-dihydroxy-6-methyl-1 : 4-dioxonaphthalene	B	1639	—	—

B, Broad band extending from 3500 cm.$^{-1}$ to beyond 2500 cm.$^{-1}$.
— Not determined.
† Compared with the dimethoxy-derivatives.
* Two bands of equal intensity.
‡ Determined by Dr. L. A. Duncanson.

As the variation in the frequency of a free phenolic hydroxyl group (3602 ± 14 cm.$^{-1}$) [22] is small compared with the frequency shifts associated with hydrogen bonding, these shifts should be a good measure of the strength of that bond. By this criterion, the indanones, where the hydroxyl band occurs at 3373 ± 5 cm.$^{-1}$, are clearly distinguished from compounds with six- or seven-membered rings, where the strongly bonded hydroxyl groups give weak broad bands, similar to that of *o*-hydroxyacetophenone,[23] whose maxima are obscured by C–H absorption bands near 2900 cm.$^{-1}$. Typical spectra are shown in Fig. 2. The weakness of the hydrogen bond in the indanones has been ascribed (above) to the greater separation of the carbonyl and the hydroxyl groups in these compounds. This separation is further increased in 4-hydroxycoumaranone and 3 : 6-dihydroxyphthalic anhydride by the presence of the shorter C–O bonds in their five-membered rings. This is reflected in their hydroxyl bands which are displaced only to 3520 cm.$^{-1}$ in the anhydride, and to 3455 cm.$^{-1}$ in the coumaranone. The weakness of the intramolecular bond in the anhydride is also revealed in the spectrum of the solid, where a strong broad band extending from 3450 to beyond 2500 cm.$^{-1}$ indicates that at least one of the hydroxyl groups forms

[22] Goulden, *Spectrochim. Acta*, 1954, **6**, 129; Ingraham, Corse, Bailey, and Stitt, *J. Amer. Chem. Soc.*, 1952, **74**, 2297.
[23] Martin, *Nature*, 1950, **166**, 474.

an intermolecular bond. In the solid indanones, and in the coumaranone, the weak but sharp peak of the chelated hydroxyl group persists. This band is, of course, largely obscured in compounds containing an additional unchelated hydroxyl group, which gives rise to a strong broad band in the solid state.[21]

Those six- and seven-membered ring compounds, which were sufficiently soluble (*i.e.*, contain only chelated hydroxyl groups), were examined in carbon tetrachloride solution, as chloroform obscures part of their broad hydroxyl absorption. That this band arises from the *peri*-hydroxyl group is clearly seen by comparing 8-hydroxy-5-methoxytetralone (Fig. 2, curve *B*) with 5 : 8-dimethoxytetralone (curve *C*). These diffuse bands bands are easily overlooked, and their presence in the spectra of these compounds does not appear to have been previously reported.[24] In general, the hydroxyl bands of the tetralones, flavanones, tetrahydrodioxonaphthalenes, and 1′ : 4′-dihydroxybenzo*cyclo*heptenedione were found to form a closely spaced group, of which curve *B* (Fig. 2) is typical, apart from variations in C–H absorption. That of 1′-hydroxy-2′ : 3′-dimethoxybenzo*cyclo*heptenone (curve *D*) is, however, clearly displaced to lower frequencies, approached only by

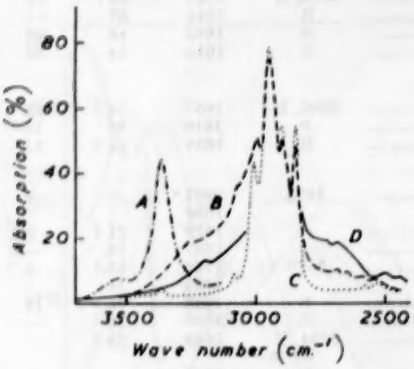


FIG. 2. *Infrared absorption curves given by* 0·1M-*solutions in* 0·4 *mm. cells :*

A, 7-*Hydroxy*-4-*methylindanone* ($CHCl_3$ *and* CCl_4 *solution*); *B*, 8-*hydroxy*-5-*methoxytetralone* (CCl_4); *C*, 5 : 8-*dimethoxytetralone* (CCl_4); *D*, 1′-*hydroxy* 2′ : 3′-*dimethoxybenzo*cyclo*heptenone* (CCl_4).

5-chloro-8-hydroxy-7-methoxytetralone. Stronger intramolecular bonds are therefore indicated in these compounds. The above distinctions are clear, but finer distinctions are difficult to make, as the absorption in this region probably includes overtone bands. For example, the overtone of the strong carbonyl absorption could always be detected between 3200 and 3300 cm.$^{-1}$.

Hunsberg and his co-workers [25] have used the drop in frequency in carbonyl groups involved in intramolecular bonds as a measure of the strength of these bonds, comparing, for example, *o*-hydroxyacetophenone with acetophenone. A similar comparison was not, in general, possible with the compounds studied here; instead, the difference between the carbonyl frequencies of the *peri*-hydroxyl and the corresponding *peri*-methoxyl compounds ($\Delta\nu$) has been measured. These differences are rather unsatisfactory, although the indanones ($\Delta\nu$ 22 $\pm$ 3 cm.$^{-1}$) are again distinguished both from 3 : 6-dihydroxyphthalic anhydride ($\Delta\nu$ 14 cm.$^{-1}$) and from the six- and seven-membered ring compounds ($\Delta\nu$ 28—67 cm.$^{-1}$). The differences between the flavanones ($\Delta\nu$ 33 and 35 cm.$^{-1}$), tetralones (37—54 cm.$^{-1}$), and benzo*cyclo*heptenones (54—67 cm.$^{-1}$) are not, however, matched by any systematic difference in their hydroxyl bands, which indicates that no general distinction can be made between the six- and seven-membered ring ketones.

The high $\Delta\nu$ values for two of the benzo*cyclo*heptenones, indeed, seem to be partly due to the abnormally high values of the carbonyl frequencies of the methylated compounds.

[24] Brockman and Frank, *Naturwiss.*, 1955, **42**, 45; Shaw and Simpson, *J.*, 1955, 655; Gardner and Horton, ref. 8.

[25] Hunsberg, *J. Amer. Chem. Soc.*, 1950, **72**, 5626; Hunsberg, Ketcham, and Gutowsky, *ibid.*, 1952, **74**, 4839.

This effect is shown in Table 2 where the 1′ : 4′-dimethoxybenzo*cyclo*heptenones and the similarly substituted indanone and tetralone are compared with their parent compounds :

TABLE 2. *Carbonyl frequencies* (cm.$^{-1}$) *in chloroform solution.*

	νCO	Substituents	νCO	Δν
Benzo*cyclo*heptenone	1672	1′ : 4′-dimethoxy-	1691	+19
Benzo*cyclo*heptene-3 : 7-dione	1689	1′ : 4′-dimethoxy-	1702	+13
Tetralone	1680	5 : 8-dimethoxy-	1680	0
Indanone	1708	4 : 7-dimethoxy-	1703	−5

The infrared data of Schubert and Sweeney [26] suggest that the carbonyl group in benzo*cyclo*heptenone is at least partially conjugated with the aromatic ring, its frequency being 33 cm.$^{-1}$ lower than that of *cyclo*heptanone. The shift to higher frequencies in the *peri*-methoxy-substituted benzo*cyclo*heptenones is then consistent with a steric effect, similar to that of *o*-methyl groups in the acetophenones,[26] forcing the carbonyl group out of the plane of the ring. That this effect does not occur with the corresponding tetralone and indanone is consistent with the greater rigidity of their five- and six-membered ketone rings.[27]

Bellamy and Beecher's [28] suggestion that the carbonyl frequencies of chelated hydroxy-ketones are themselves a good measure of strength of hydrogen bonding seems to be roughly true, since, apart from 1′-hydroxy-2′ : 3′-dimethoxybenzo*cyclo*heptenone, all the six- and seven-membered ring compounds absorb between 1637 and 1648 cm.$^{-1}$. *o*-Hydroxy-acetophenone, too, absorbs in this range, *i.e.*, at 1648 cm.$^{-1}$ in carbon tetrachloride solution,[25] in which these carbonyl frequencies have been found to be about 3 cm.$^{-1}$ higher. The benzo*cyclo*heptenone, which absorbs at 1616 cm.$^{-1}$, is also clearly distinguished by its hydroxyl absorption. A low carbonyl frequency (near 1622 cm.$^{-1}$) has also been reported for 1′-hydroxy-2′ : 3′ : 4-trimethoxybenzo*cyclo*hepten-3-one ; [9] this implies partial bond fixation in the aromatic rings.

The markedly higher carbonyl frequencies of the indanones (1678—1686 cm.$^{-1}$) are, of course, partly due to the ring-strain effect,[21] which cannot be allowed for with any precision.

EXPERIMENTAL

The infrared measurements were made on 0·02M-solutions in chloroform, except where otherwise stated, with a Grubb-Parsons Double-beam spectrometer, type S4, equipped with a sodium chloride prism. The frequency scale was calibrated against phenol in carbon tetrachloride [29] and polystyrene film [30] in the 3000 cm.$^{-1}$ region (accuracy ± 10 cm.$^{-1}$) and by water-vapour bands in the 1600—1850 cm.$^{-1}$ region (accuracy ± 2 cm.).$^{-1}$

Methylations with Diazomethane.—General procedure : To a solution of the hydroxy-compound in a suitable solvent, ethereal diazomethane (ten-fold excess) was added. The mixture was kept in ice overnight, the solvent removed, and the residue crystallised from light petroleum.

4 : 7-*Dimethoxy*-3-*methylindanone.*—4 : 7-Dihydroxy-3-methylindanone (0·5 g.) was refluxed for 2 hr. with methyl sulphate (3·6 g.), acetone (10 ml.), and anhydrous potassium carbonate (7 g.). After dilution with water the *product* was taken into ether and distilled at 200°/0·05 mm., to give a solid which crystallised from light petroleum (b. p. 50—60°) in rosettes, m. p. 73° (Found : C, 69·7; H, 6·65. $C_{12}H_{14}O_3$ requires C, 69·9; H, 6·8%).

1′ : 4′-*Dimethoxybenzo*cyclo*hepten*-3-*one.*—Methylation of the 1′ : 4′-dihydroxy-compound with methyl sulphate, as above, gave the *dimethyl ether* as needles, m. p. 60° (from light petroleum) (Found : C, 70·8; H, 7·55. $C_{12}H_{14}O_3$ requires C, 70·9; H, 7·3%).

3 : 4-*Diacetoxybenzofuran.*—A mixture of 4-hydroxycoumaran-3-one (0·2 g.), acetic anhydride (0·5 ml.), and a trace of sulphuric acid was boiled for 5 min. The *diacetate* formed prisms, m. p. 61° (from light petroleum) (Found : C, 61·7; H, 4·3. $C_{12}H_{10}O_5$ requires C, 61·6; H, 4·3%).

[26] Schubert and Sweeney, *ibid.*, 1955, **77**, 4172.
[27] Braude and Sondheimer, *J.*, 1955, 3754.
[28] Bellamy and Beecher, *J.*, 1954, 4487.
[29] Fox and Martin, *Proc. Roy. Soc.*, 1937, *A*, **162**, 419; also ref. 22.
[30] Plyler and Peters, *J. Res. Nat. Bur. Stand.*, 1950, **45**, 462.

5 : 7-*Dihydroxychromanone*.—5 : 7-Dimethoxychromanone (100 mg.) and 48% hydrobromic acid (5 ml.) were refluxed for 1½ hr. Dilution with water and ether-extraction gave a solid *phenol* which crystallised from water in slender needles, m. p. 230° (Found : C, 59·8; H, 4·7. $C_9H_8O_4$ requires C, 60·0; H, 4·4%). The *diacetate* separated from light petroleum in needles, m. p. 102° (Found : C, 59·0; H, 4·45. $C_{13}H_{12}O_6$ requires C, 59·1; H, 4·55%).

5 : 7 : 8-*Trimethoxy-2-methyl-1-tetralone* (with J. F. GARDEN).—Anhydrous aluminium chloride (80 g.) was added, during 75 min., to a mixture of 1 : 2 : 4-trimethoxybenzene (50 g.) and methylsuccinic anhydride (33 g.) in *s*-tetrachlorethane (320 ml.), stirred (Hg seal) at 0—5°.

No.	Hydroxy-carbonyl compound	Solvent	Product	M. p.
1	4-Hydroxycoumaran-3-one	Chloroform	4-Methoxy	151°
2	4 : 6-Dihydroxycoumaran-3-one	Dioxan	4-Methoxy [a]	290
		Tetrahydrofuran	4 : 6-Dimethoxy	136
3	3 : 6-Dihydroxyphthalic anhydride	Acetone	3 : 6-Dimethoxy	264
4	3 : 6-Dihydroxyphthalimide	Acetone	3 : 6-Dimethoxy-*N*-methyl	192
5	3-Hydroxyphthalimide	Dioxan	3-Methoxy-*N*-methyl	144
6	7-Hydroxyphthalide	Ether	7-Methoxy	108 *
7	7-Hydroxyindanone	Ether	7-Methoxy	106
8	7-Hydroxy-3-methylindanone	Ether	7-Methoxy	55
9	7-Hydroxy-4-methylindanone	Ether	7-Methoxy	112
10	7-Hydroxy-3 : 4-dimethylindanone	Ether	7-Methoxy	77
11	4-Chloro-7-hydroxyindanone	Ether	7-Methoxy	148
12	4-Chloro-7-hydroxy-3-methylindanone	Ether	7-Methoxy	94
13	5 : 7-Dihydroxychromanone	Ether	7-Methoxy	76

	Found (%)				Required (%)		
No.	C	H	N or Cl	Formula	C	H	N or Cl
1	65·4	4·9	—	$C_9H_8O_3$	65·7	5·0	—
4	59·9	4·85	6·4	$C_{11}H_{11}O_4N$	59·7	5·0	6·3
5	62·5	4·8	7·3	$C_{10}H_9O_3N$	62·8	4·9	7·3
6	65·7	4·85	—	$C_9H_8O_3$	65·8	4·9	—
7	74·2	6·4	—	$C_{10}H_{10}O_2$	74·1	6·5	—
10	76·2	6·9	—	$C_{12}H_{14}O_2$	76·4	6·9	—
11	60·9	4·4	Cl 17·6	$C_{10}H_9O_2Cl$	61·1	4·6	Cl 18·0
12	62·6	5·2	Cl 16·3	$C_{11}H_{11}O_3Cl$	62·8	5·2	Cl 16·7
13	61·6	5·05	—	$C_{10}H_{10}O_4$	61·85	5·15	—

* Duncanson, Grove, and Zealley (*J.*, 1953, 1333) record m. p. 96°. This is probably due to incomplete separation from 4-methoxyphthalide formed simultaneously in their method of preparation.

After a further hour's stirring, the mixture was left at *ca.* 10° for 2 days and then allowed to warm to room temperature. Addition of ice (300 g.) and concentrated hydrochloric acid (200 ml.), followed by removal of the solvent in steam, left an oil which solidified. This was extracted with 10% aqueous sodium carbonate and filtered, the residue was washed with hot water, and the combined alkaline solutions were cooled in ice and acidified. The crude keto-acids were collected, dried, and taken up in the minimum of hot ethanol from which *α-methyl-β-(2 : 4 : 5-trimethoxybenzoyl)propionic acid* separated in prisms, m. p. 161° (25·5 g.) (Found : C, 60·1; H, 6·7. $C_{14}H_{18}O_6$ requires C, 59·6; H, 6·4%). Oxidation of this with alkaline permanganate gave 2 : 4 : 5-trimethoxybenzoic acid, m. p. and mixed m. p. 144°. The position of the methyl group in the acid of m. p. 161° was not proved.[31] Evaporation of the ethanol mother-liquor left an oil which crystallised from benzene (charcoal) and then from aqueous ethanol, yielding *β-methyl-β-(2 : 4 : 5-trimethoxybenzoyl)propionic acid* in needles, m. p. 125—126° (8 g.) (Found : C, 59·8; H, 6·5. $C_{14}H_{18}O_6$ requires C, 59·6; H, 6·4%).

Clemmensen reduction of the keto-acid, m. p. 161°, gave *α-methyl-γ-(2 : 4 : 5-trimethoxyphenyl)butyric acid* which separated from light petroleum (b. p. 50—60°) in leaflets, m. p. 62° (Found : C, 62·65; H, 7·3. $C_{14}H_{20}O_5$ requires C, 62·65; H, 7·5%). This acid (3 g.) was stirred into polyphosphoric acid (30 g.) at 60°. After 30 min. the red mixture was poured on ice. The *tetralone* crystallised from light petroleum (b. p. 80—90°) in sheaves, m. p. 118° (95%) (Found : C, 67·0; H, 7·0. $C_{14}H_{18}O_4$ requires C, 67·2; H, 7·25%). The *semicarbazone* formed needles, m. p. 220° (from ethanol) (Found : N, 13·8. $C_{15}H_{21}O_4N_3$ requires N, 13·7%).

Clemmensen reduction and cyclisation of the keto-acid, m. p. 126°, gave **5 : 7 : 8-*trimethoxy-3-methyltetralone*** in needles, m. p. 112—113° (from light petroleum) (Found : C, 66·95; H, 7·0.

[31] Berliner in "Organic Reactions," Wiley, New York, 1949, Vol. V, p. 242.

$C_{14}H_{18}O_4$ requires C, 67·2; H, 7·25%), which formed a *semicarbazone*, needles, m. p. 236° (from ethanol) (Found: N, 13·9. $C_{15}H_{21}O_4N_3$ requires N, 13·7%).

8-Hydroxy-5 : 7-dimethoxy-2-methyl-1-tetralone.—The trimethoxytetralone (0·5 g.) (above) in glacial acetic acid (5 ml.) was refluxed for 2 hr. with concentrated hydrochloric acid (20 ml.) and poured into water. The *hydroxy-ketone* was collected and crystallised from light petroleum in bright, yellow needles, m. p. 89° (Found: C, 66·15; H, 6·6. $C_{13}H_{16}O_4$ requires C, 66·1; H, 6·8%). The *acetate* formed pale yellow needles, m. p. 141° (from light petroleum) (Found: C, 64·75; H, 6·3. $C_{15}H_{18}O_5$ requires C, 64·8; H, 6·5%).

Reactions with Phenyl iso*Cyanate.*—General procedure: A solution of the hydroxy-compound (0·2 g.) in light petroleum (20 ml., b. p. 100—120°) was refluxed for 2 hr. with an equimolecular portion of phenyl *iso*cyanate and a few drops of triethylamine. The urethane separated on cooling and was recrystallised from the same solvent or from acetic acid. The results, tabulated, include some miscellaneous compounds which are new.

New urethanes.

No.	Hydroxy-ketone	Urethane	M. p.
1	4 : 7-Dihydroxy-3-methylindanone	4-Mono	158°
2	5 : 8-Dihydroxy-4-methyltetralone	5-Mono	152
3	1′ : 4′-Dihydroxy-7-methylbenzo*cyclo*hepten-3-one	1′ : 4′-Di	220
4	1′ : 4′-Dihydroxybenzo*cyclo*heptene-3 : 7-dione	1′ : 4′-Di	182
5	*o*-Fluorophenol	—	104
6	2-Hydroxydiphenyl sulphide	—	119
7	2-Hydroxydiphenyl sulphone	—	127
8	1-*p*-Tolylthio-2-naphthol	—	153
9	1-Toluene-*p*-sulphonyl-2-naphthol	—	152

	Found (%)					Required (%)			
No.	C	H	N	S	Formula	C	H	N	S
1	67·8	4·9	5·1	—	$C_{17}H_{15}O_4N$	67·6	5·1	4·9	—
2	69·3	5·3	4·3	—	$C_{18}H_{17}O_4N$	69·5	5·5	4·5	—
3	68·9	5·7	6·35	—	$C_{26}H_{24}O_6N_2$	70·25	5·45	6·3	—
4	67·2	4·8	6·3	—	$C_{26}H_{20}O_6N_2$	67·5	4·5	6·3	—
5	67·3	4·5	5·85	—	$C_{12}H_{10}O_3NF$	67·5	4·4	6·05	—
6	71·5	4·7	4·4	9·7	$C_{19}H_{15}O_3NS$	71·6	4·6	4·4	10·0
7	63·3	4·3	3·7	9·7	$C_{19}H_{15}O_4NS$	63·6	4·4	4·1	9·3
8	74·9	4·8	3·5	8·4	$C_{24}H_{19}O_3NS$	74·8	4·9	3·6	8·3
9	68·8	4·5	3·7	7·8	$C_{24}H_{19}O_4NS$	69·1	4·5	3·4	7·7

We thank Dr. L. A. Duncanson for some preliminary infrared data, Imperial Chemical Industries Limited, Nobel Division, for the molecular-weight determinations, and Professors W. Cocker, R. D. Haworth, F.R.S., and T. R. Seshadri, Dr. W. J. Horton, and Mrs. J. Zealley for samples of hydroxy-ketones. One of us (N. F. H.) is grateful to the Department of Scientific and Industrial Research for a Maintenance Allowance.

Chemistry Department, The University, Old Aberdeen.
The Macaulay Institute for Soil Research,
Craigiebuckler, Aberdeen.

[*Received, April 3rd,* 1956.]

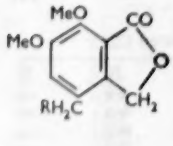
695. *Lactones. Part III.* A Further Example of Alkyl–Oxygen Bond Fission in Phthalide Ring Opening.*

By John Blair, W. R. Logan, and G. T. Newbold.

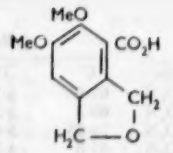
Dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)-malonate, obtained by interaction of 4-chloromethylmeconin and methyl malonate, though normally hydrolysed by aqueous alkali to the corresponding lactone dicarboxylic acid, is isomerised by methanolic sodium methoxide to 5 : 6-dimethoxy-2 : 2-di(methoxycarbonyl)indane-4-carboxylic acid. The mechanism of the rearrangement is discussed.

The conversion of a 4-hydroxymethylphthalide (*e.g.*, I; R = OH) into the isomeric phthalan-4-carboxylic acid [1] (*e.g.*, II) has been examined by Blair and Newbold [2] who reported that methanolic sodium methoxide was a very effective isomerising agent. A mechanism for the rearrangement using this base was proposed [2] envisaging the participation of a carbonium ion formed by fission of the phthalide ring with rupture of the methylene–oxygen bond, *i.e.*, B_{AL} fission.[3]

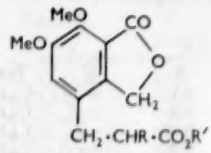
This hypothesis of the formation of a carbonium ion being used it seemed of interest to endeavour to effect its union with a suitable carbanion, such as that derived from a malonic ester. No evidence of any competing reaction was forthcoming when 4-hydroxymethylmeconin (I; R = OH) was heated with an excess of methyl sodiomalonate;



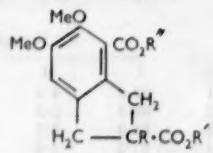
(I)



(II)



(III)



(IV)

only the normal rearrangement product 5 : 6-dimethoxyphthalan-4-carboxylic acid (II) was isolated. Attention was then turned to a possible intramolecular reaction between a carbonium ion from B_{AL} phthalide fission and a carbanion from a suitably placed α-substituted malonic ester in the same molecule; such a molecule was dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (III; R = CO_2Me, R′ = Me).

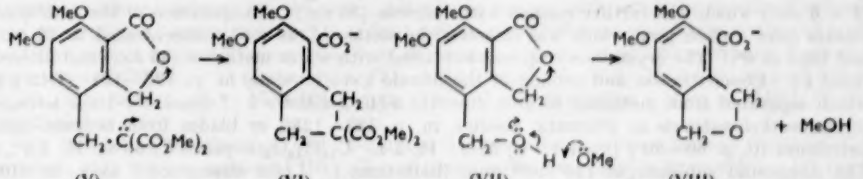
Reaction of equimolecular proportions of 4-chloromethylmeconin (I; R = Cl) and methyl sodiomalonate gave as major product this ester (III; R = CO_2Me, R′ = Me), the other constituent of the neutral fraction being the corresponding αα-di-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate. The latter ester was characterised by hydrolysis to the malonic acid which gave back the original ester on treatment with diazomethane. The ester (III; R = CO_2Me, R′ = Me) was insoluble in aqueous sodium hydrogen carbonate and when heated with aqueous sodium hydroxide was hydrolysed to α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonic acid (III; R = CO_2H, R′ = H) which with diazomethane gave back the ester (III; R = CO_2Me, R′ = Me); hence no change in the carbon skeleton had taken place on the aqueous alkaline treatment. The acid (III; R = CO_2H, R′ = H) was smoothly decarboxylated to β-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furyl)propionic acid (III; R = R′ = H) which showed infrared bands at 1754 (phthalide-carbonyl stretching frequency), 1698 (carboxylic acid), and 1613 cm.$^{-1}$ (aromatic ring); its methyl ester (III; R = H, R′ = Me) showed bands at 1750 (phthalide-carbonyl stretching frequency) and 1718 cm.$^{-1}$ (methoxycarbonyl group), both determinations being effected in Nujol mull.

* Part II, *J.*, 1955, 2871.

[1] Brown and Newbold, *J.*, 1952, 4878.
[2] Blair and Newbold, *J.*, 1954, 3935.
[3] Ingold, "Structure and Mechanism in Organic Chemistry," Bell, London, 1953, p. 752 *et seq.*

Dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (III; R = CO_2Me, R′ = Me), when heated in methanol with 1 mol. of sodium methoxide, was isomerised to 5 : 6-dimethoxy-2 : 2-di(methoxycarbonyl)indane-4-carboxylic acid (IV; R = CO_2Me, R′ = Me, R″ = H). The latter compound was also obtained from the acid fraction of the reaction product from 4-chloromethylmeconin and methyl sodiomalonate. Alkaline hydrolysis of the acid gave 5 : 6-dimethoxyindane-2 : 2 : 4-tricarboxylic acid (IV; R = CO_2H, R′ = R″ = H), esterified by diazomethane to the trimethyl ester (IV; R = CO_2Me, R′ = R″ = Me) which was also obtained by the same treatment of the acid ester (IV; R = CO_2Me, R′ = Me, R″ = H). When dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (III; R = CO_2Me, R′ = Me) was heated with an excess of methanolic sodium methoxide a dicarboxylic acid, $C_{15}H_{16}O_8$, was formed; we formulate this compound as 5 : 6-dimethoxy-2-methoxycarbonylindane-2 : 4-dicarboxylic acid (IV; R = CO_2Me, R′ = R″ = H) since on hydrolysis it gave the tricarboxylic acid (IV; R = CO_2H, R′ = R″ = H) and on esterification with diazomethane the triester (IV; R = CO_2Me, R′ = R″ = Me). The formation of the dicarboxylic acid presumably proceeds *via* the monoacid (IV; R = CO_2Me, R′ = Me, R″ = H) by hydrolysis effected by the traces of water in the redistilled commercial methanol used as solvent.

5 : 6-Dimethoxyindane-2 : 2 : 4-tricarboxylic acid was smoothly decarboxylated by heat, to give 5 : 6-dimethoxyindane-2 : 4-dicarboxylic acid (IV; R = R′ = R″ = H) which shows infrared bands in Nujol mull at 1695 (carboxylic acid) and 1592 cm.$^{-1}$ (aromatic ring).



(V) (VI) (VII) (VIII)

Reaction of 4-chloromethylmeconin with ethyl sodiomalonate gave two solid products, (III; R = CO_2Et, R′ = Et) and the corresponding αα-disubstituted malonate. The former product on aqueous-alkaline hydrolysis gave the diacid (III; R = CO_2H, R′ = H) and on treatment with sodium ethoxide followed by hydrolysis of the acidic fraction of the reaction product gave the indane triacid (IV; R = CO_2H, R′ = R″ = H).

Electrometric titrations have been carried out on all the acids described above and, except that for (III; R = CO_2H, R′ = H), which was 6% high, the results agree closely with the calculated values of the equivalents, thus supporting the structures assigned. In their ultraviolet spectra the compounds in the phthalide series (III; R = CO_2Me, R′ = Me; R = CO_2H, R′ = H; R = R′ = H; and R = H, R′ = Me) exhibit a band at 3110—3130 Å (cf. in meconin [1] at 3080 Å) whereas the compounds in the indane series (IV; R = CO_2Me, R′ = Me, R″ = H; R = CO_2Me, R′ = R″ = H; R = CO_2H, R′ = R″ = H; and R = R′ = R″ = H) show a band at 2960—2990 Å [cf. *o*-veratric acid which shows light absorption in ethanol with maxima at 2100 (ε 20,200) and 2950 Å (ε 2100)]; this difference in spectra supports the respective structures.

Though we have used the carbonium–carbanion union as a working hypothesis we consider that the mechnism of the conversion of the phthalide-malonic ester to the indane derivative is best represented by (V) ⟶ (VI), *i.e.*, as a concerted electron-transfer. It is difficult to visualise B_{AL} phthalide fission which, while initiated by the methoxide ion, is not followed by reaction of the carbonium ion to form a methyl ether, as in the $B_{AL}2$ (S_N2) reaction of methyl benzoate with methoxide ion to give dimethyl ether and benzoate ion.[4] It follows that the hydroxymethylphthalide–phthalancarboxylic acid rearrangement is represented by (VII) ⟶ (VIII).

These mechanisms still involve B_{AL} fission of the phthalide ring but avoid the difficulties

[4] Bunnett, Robison, and Pennington, *J. Amer. Chem. Soc.*, 1950, **72**, 2378.

associated with initial carbonium-ion formation. The hydroxymethylphthalide–phthalancarboxylic acid rearrangement is also brought about by aqueous sodium carbonate, a reagent less effective than sodium methoxide but much more effective than sodium hydroxide.[2] The carbonate-induced reaction may involve carbonium-ion formation ($B_{AL}1$ fission) as an initial step, support being given for this by the experiences of Kenyon *et al.*[5] in the hydrolysis of methylphenylallyl alcohols by sodium carbonate and hydroxide. The remaining stage of the reaction could then follow Blair and Newbold's scheme.[2]

Experimental

Ultraviolet absorption spectra were determined for EtOH solutions; equivalents were determined in water under nitrogen according to the method of Catch, Cook, and Kitchener.[6] Redistilled commercial methanol was used in all experiments.

Dimethyl α-(1 : 3-*Dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furylmethyl*)*malonate*.—A solution of 4-chloromethylmeconin (4·85 g.) in warm methanol (55 c.c.) was added in one portion to methanolic methyl sodiomalonate prepared from the ester (2·64 g.), methanol (25 c.c.), and sodium (0·46 g.). The solution was refluxed for 3 hr., rapid separation of sodium chloride being observed. The mixture was concentrated under reduced pressure, and the residue diluted with water (25 c.c.) and extracted with chloroform (3 × 30 c.c.). The combined extracts were washed with 10% aqueous sodium hydrogen carbonate (2 × 30 c.c.) (combined extract A), then water, and dried (Na_2SO_4). Evaporation of the chloroform gave a clear yellow gum (5·72 g.) which partially solidified. The crystals (solid B) were separated by addition of benzene (25 c.c.) and filtration. The filtrate was percolated through a column of Grade II alumina (2 × 6 cm.) which was further washed with benzene (50 c.c.). Evaporation of the combined eluates gave a clear gum which was dissolved in methanol (36 c.c.), concentrated to 12 c.c., and kept at 0°. The crystalline crop was extracted with warm methanol (35 c.c.) and filtered (solid C). Concentration and cooling of the filtrate gave crystals, m. p. 122—124° (1·42 g.), which separated from methanol to give *dimethyl* α-(1 : 3-*dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*-[c]*furylmethyl*)*malonate* as prismatic needles, m. p. 123—125°, or blades from benzene–light petroleum (b. p. 60—80°) (Found : C, 57·0; H, 5·4. $C_{16}H_{18}O_8$ requires C, 56·8; H, 5·4%). The compound sublimes at 130°/10^{-4} mm. (bath-temp.). Light absorption : max. at 2100 (ε 48,000) and 3110 Å (ε 5600).

Dimethyl αα-Di-(1 : 3-*Dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furylmethyl*)*malonate*.—Solids B (195 mg.; m. p. 186—191°) and C (182 mg.; m. p. 192—193°) from the preceding experiment were combined and crystallised from benzene, to give the *ester* (340 mg.) as needles, m. p. 197—198° (Found : C, 59·5, 59·8; H, 5·5, 5·2; OMe, 34·3. $C_{27}H_{28}O_{12}$ requires C, 59·55; H, 5·2; 6OMe, 34·2%).

Reaction of 4-*Chloromethylmeconin with Ethyl Malonate*.—The same molar proportions being used as in the methyl malonate reaction, 4-chloromethylmeconin (6·0 g.) was refluxed for 2 hr. with ethanolic ethyl sodiomalonate. Isolation by use of chloroform gave a neutral fraction (5·9 g.), m. p. 80—100°. Crystallisation from benzene gave as the component of smaller solubility *diethyl αα-di*-(1 : 3-*dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furylmethyl*)*malonate* (1·5 g.) which separated as needles, m. p. 168—169·5° (Found : C, 61·1; H, 5·6. $C_{29}H_{32}O_{12}$ requires C, 60·8; H, 5·6%). Fractional crystallisation of the material in the benzene mother-liquors gave the more soluble component, *diethyl* α-(1 : 3-*dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furyl-methyl*)*malonate* (1·1 g.) which separated from benzene–light petroleum (b. p. 60—80°) as needles, m. p. 114—115° (Found : C, 58·9; H, 6·1. $C_{18}H_{22}O_8$ requires C, 59·0; H, 6·05%). Light absorption : Max. at 2080 (ε 44,000) and 3100 Å (ε 4300). No crystalline material was obtained from the bicarbonate-soluble fraction (0·5 g.).

αα-Di-(1 : 3-*dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furylmethyl*)*malonic Acid*.—Dimethyl αα-di-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (50 mg.) was refluxed in a mixture of ethanol (2·5 c.c.) and 2N-aqueous sodium hydroxide (2·5 c.c.) for 2 hr. Removal of ethanol and acidification (Congo-red) with hydrochloric acid gave the *acid* (35 mg.) which separated from aqueous acetone as needles, m. p. 228° (Found : C, 58·2; H, 4·8%; equiv., 245. $C_{25}H_{24}O_{12}$ requires C, 58·1; H, 4·7%; equiv., 258). Esterification with diazomethane gave the dimethyl ester as needles, m. p. and mixed m. p. 197—198°, from benzene. The same acid was obtained by hydrolysis of the diethyl ester and separated from aqueous acetone as needles, m. p. and mixed m. p. 228°.

[5] Kenyon, Partridge, and Phillips, *J.*, 1936, 85; 1937, 207.
[6] Catch, Cook, and Kitchener, *J.*, 1945, 319.

α-(1 : 3-*Dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furylmethyl*)*malonic Acid*.—(*a*) Dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (100 mg.) was heated under reflux with 2N-aqueous sodium hydroxide (4 c.c.) for 1 hr. The cooled solution was acidified (Congo-red) with concentrated hydrochloric acid. The crystalline precipitate was separated and crystallised from water, to give the *acid* (80 mg.) as plates, m. p. 153—155° (decomp.) (Found : C, 54·1; H, 4·9%; equiv., 165. $C_{14}H_{14}O_8$ requires C, 54·2; H, 4·55%; equiv., 155). Light absorption : Max. at 2100 (ε 30,000) and 3130 Å (ε 4450).

(*b*) By the same method the corresponding diethyl ester gave the acid, as plates (from water), m. p. 153—155° (decomp.) alone or mixed with preparation (*a*).

Treatment of the acid with excess of ethereal diazomethane followed by evaporation and crystallisation of the residue from methanol gave dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate as prismatic needles, m. p. and mixed m. p. 123—125°.

β-(1 : 3-*Dihydro*-6 : 7-*dimethoxy*-1-*oxo*-4-*benzo*[c]*furyl*)*propionic Acid*.—α-(1 : 3-Dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonic acid (100 mg.) was heated at 190—200° (bath-temp.) at atmospheric pressure until decarboxylation was complete and the residue sublimed at 170—180°/10^{-3} mm. (bath-temp.), to give the *acid* (70 mg.) which separated from methanol as flat prisms, m. p. 166—168° (Found : C, 58·5; H, 5·5%; equiv., 264. $C_{13}H_{14}O_6$ requires C, 58·6; H, 5·3%; equiv., 266). Light absorption : Max. at 2100 (ε 33,500) and 3120 Å (ε 4750). The *methyl ester*, prepared by using ethereal diazomethane, separated from aqueous methanol as flat prisms, m. p. 93—94° (Found : C, 60·15; H, 6·1. $C_{14}H_{16}O_6$ requires C, 60·0; H, 5·75%). Light absorption : Max. at 2130 (ε 30,000) and 3120 Å (ε 4600).

5 : 6-*Dimethoxy*-2 : 2-*di*(*methoxycarbonyl*)*indane*-4-*carboxylic Acid*.—(*a*) The sodium hydrogen carbonate extract A (above) was acidified (Congo-red) with concentrated hydrochloric acid and extracted with chloroform (3 × 50 c.c.). After being washed with water the combined extract was dried ($NaSO_4$) and evaporated to a light yellow gum (750 mg.) which was triturated with cold methanol (5 c.c.), and the resulting solid separated. Crystallisation from aqueous methanol gave the *acid* (300 mg.) as blades, m. p. 131—132° (Found : C, 57·2; H, 5·5%; equiv., 337·5. $C_{16}H_{18}O_8$ requires C, 56·8; H, 5·4%; equiv., 338). Light absorption : Max. at 2110 (ε 25,700 and 2980 Å (ε 4200).

(*b*) A solution of dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)-malonate (338 mg.) in methanol (10 c.c.) containing sodium methoxide from sodium (23 mg.; 1 equiv.) was refluxed for 8 hr. The solution was evaporated under reduced pressure, the residue treated with water (15 c.c.) (partial solution), and the mixture extracted with chloroform (3 × 25 c.c.). The acid fraction was isolated by means of sodium hydrogen carbonate as in (*a*), to give 5 : 6-dimethoxy-2 : 2-di(methoxycarbonyl)indane-4-carboxylic acid (190 mg.) which separated from aqueous methanol as blades, m. p. 130—131·5° alone or mixed with preparation (*a*). Unchanged material (100 mg.), prismatic needles (from methanol), m. p. and mixed m. p. 121—123°, was obtained from the neutral fraction.

5 : 6-*Dimethoxy*-2-*methoxycarbonylindane*-2 : 4-*dicarboxylic Acid*.—A solution of dimethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (1·0 g.) in methanol (25 c.c.) containing sodium methoxide [from sodium (0·55 g.)] was refluxed for 9 hr., concentrated under reduced pressure, and diluted with water. Isolation of the acid fraction through chloroform and sodium hydrogen carbonate gave an amber gum (900 mg.), which solidified. Trituration with dry ether, filtration from a trace of insoluble material, concentration of the filtrate, and treatment with light petroleum (b. p. 40—60°) gave a solid, two crystallisations of which from ether–light petroleum (b. p. 40—60°) gave the *acid* (500 mg.) as prismatic needles, m. p. 163—165° (Found : C, 55·85; H, 5·2%; equiv., 168. $C_{15}H_{16}O_8$ requires C, 55·55; H, 5·0%; equiv., 162). Light absorption : Max. at 2090 (ε 19,000) and 2990 Å (ε 3600).

5 : 6-*Dimethoxyindane*-2 : 2 : 4-*tricarboxylic Acid*.—(*a*) 5 : 6-Dimethoxy-2 : 2-di(methoxycarbonyl)indane-4-carboxylic acid (250 mg.) was heated on the steam-bath for 1 hr. with 2N-aqueous sodium hydroxide (5 c.c.). The cooled solution was made acid (Congo-red) with hydrochloric acid (*d* 1·15), and the precipitate collected. Crystallisation from water gave 5 : 6-*dimethoxyindane*-2 : 2 : 4-*tricarboxylic acid* (190 mg.) as prismatic needles, m. p. 185—187° (decomp.) (Found : C, 54·5; H, 4·8%; equiv., 103. $C_{14}H_{14}O_8$ requires C, 54·2; H, 4·55%; equiv., 103). Light absorption : Max. at 2080 (ε 25,800) and 2975 Å (ε 3900). The same acid, m. p. and mixed m. p. 185—187°, was obtained by hydrolysis of 5 : 6-dimethoxy-2-methoxycarbonylindane-2 : 4-dicarboxylic acid.

(*b*) Diethyl α-(1 : 3-dihydro-6 : 7-dimethoxy-1-oxo-4-benzo[*c*]furylmethyl)malonate (1·25 g.) was added to a warm solution of sodium ethoxide in dry ethanol (25 c.c.) [from sodium (0·7 g.)]. The yellow solution was refluxed for 8 hr., concentrated to small bulk under reduced pressure,

diluted with water, and acidified (Congo-red) with hydrochloric acid (*d* 1·15). The acid fraction, a clear light brown gum (1·0 g.), was isolated by using chloroform and aqueous sodium hydrogen carbonate. Hydrolysis of the gum, which did not solidify, as in (*a*) gave the acid (0·55 g.), crystallising from water as prismatic needles, m. p. 185—187° alone or mixed with preparation (*a*) (Found: C, 54·4; H, 4·7%).

Methyl 5 : 6-Dimethoxyindane-2 : 2 : 4-tricarboxylate.—5 : 6-Dimethoxy-2 : 2-di(methoxycarbonyl)indane-4-carboxylic acid (100 mg.) in methanol (5 c.c.) was treated with excess of ethereal diazomethane and kept overnight. Removal of solvent and crystallisation from benzene–light petroleum (b. p. 40—60°) gave the *ester* as prisms, m. p. 78·5—80·5° (Found: C, 58·3; H, 6·0. $C_{17}H_{20}O_8$ requires C, 57·95; H, 5·7%). Light absorption: Max. at 2080 (ε 21,500) and 2990 Å (ε 4200). The same ester, m. p. and mixed m. p. 78·5—80·5°, was obtained by the action of diazomethane on 5 : 6-dimethoxyindane-2 : 2 : 4-tricarboxylic or 5 : 6-dimethoxy-2-methoxycarbonylindane-2 : 4-dicarboxylic acid.

5 : 6-Dimethoxyindane-2 : 4-dicarboxylic Acid.—5 : 6-Dimethoxyindane-2 : 2 : 4-tricarboxylic acid (100 mg.) was heated at 200—210° (bath-temp.) under atmospheric pressure until no further evolution of carbon dioxide took place. Sublimation at 160°/10^{-4} mm. followed by crystallisation from ethyl acetate–light petroleum (b. p. 40—60°) gave *5 : 6-dimethoxyindane-2 : 4-dicarboxylic acid* (60 mg.) as prisms, m. p. 153·5—155° (Found: C, 59·1; H, 5·5%; equiv., 131. $C_{13}H_{14}O_6$ requires C, 58·6; H, 5·3%; equiv., 133). Light absorption: Max. at 2100 (ε 23,000) and 2960 Å (ε 3900).

We wish to acknowledge helpful discussions with our colleagues, particularly Professor F. S. Spring, F.R.S., and Dr. D. C. Munro.

The Royal Technical College, Glasgow. [*Received, April 9th*, 1956.]

---

696. *The Preparation of Active Solids by Thermal Decomposition. Part IX.* The Calcination of Hydrous Ferric Oxide and of Lepidocrocite.*

By J. F. Goodman and S. J. Gregg.

Calcination studies have been made of three materials, a precipitated ferric oxide gel slightly contaminated with chloride ions, one grossly contaminated with sulphate ions (probably as basic sulphate), and lepidocrocite (γ-FeO·OH): separate samples of each have been heated for five hours at a succession of fixed temperatures between 25° and 1100°, and a number of properties of the product have been examined, including the surface area by sorption of nitrogen, the density by immersion in water or in carbon tetrachloride, the lump volume by immersion in mercury, *X*-ray diffraction, and electron micrograph. The original material was also submitted to thermogravimetric analysis and to extensometric examination, both with a steadily rising temperature.

Results show that the first gel, a hydrous oxide, does not become activated when it loses water as the temperature of calcination is raised, but progressively diminishes in specific surface; lepidocrocite does show an increase in specific surface when it decomposes but the increase is small probably because the change in lattice is slight; the decomposition probably involves merely a shrinkage in thickness but not in diameter of plate-like particles. The sulphated gel increases in pore volume but not in surface when the sulphur trioxide is expelled at 700°, indicating that the SO_3 vacancies migrate to the surface of the micelles and coalesce there. All three substances, as well as the pure ferric oxide gel of Part II,[1] show an enhanced rate of sintering when a temperature at or near the Tammann temperature is reached.

In Part II [1] the effect of calcination on a hydrous ferric oxide (say batch A) was studied. From the results it seemed that the region around and above the Tammann temperature was of particular interest and should repay detailed examination. (The Tammann temperature is one-half of the melting temperature expressed in °K. Fe_2O_3 melts, with some

* Part VIII, *J.*, 1956, 1506.

[1] Gregg and Hill, *J.*, 1953, 3945.

decomposition to Fe_3O_4, at 1730° K; its true melting point probably lies somewhat above this temperature and below that of Fe_3O_4, *viz.*, 1870° K. The Tammann temperature of Fe_2O_3 probably lies therefore between 600° and 660° C.) It happened that two other batches which had been prepared at about the same time as batch A were available, one (say batch B) containing slightly more chloride impurity than A, and the other (C) grossly contaminated with sulphate ions; these offered the further opportunity to study the effect of ionic contamination on the sintering behaviour of an active oxide, thereby representing an extension of the work of Parts VI and VII.[2,3] Further, in order to compare the behaviour of the hydrous oxides with that of a corresponding substance containing combined "water," lepidocrocite (γ-FeO·OH) was included in the study.

The procedure was much the same as in previous Parts, *viz.*, to prepare a "calcination series" from each batch by heating separate portions of it for 5 hours at different fixed temperatures within the range 25—1100°, and then to examine certain properties of the cooled product. In addition, separate portions of the starting material of each batch were subjected to thermogravimetric analysis on the thermal balance, and to extensometric examination, both with temperature rising at a constant rate.

Experimental

Materials.—The preparation of batch A is described in detail in Part II,[1] whence it will be seen that the precipitate, prepared from the chloride, has been formed in extremely dilute solution and washed many times. Batch B represents an earlier stage in the washing of batch A, and it had a chloride content of 0·15%, as compared with the 0·04% found for A (of Gregg and Hill,[1] *viz.*, 0·015—0·03%).

Batch C had been prepared [4] by precipitating saturated ferric ammonium sulphate solution with 11·2% potassium hydroxide solution in slight excess. The gel was washed by decantation till the supernatant solution failed to give any reaction for sulphate ions; it was then filtered at the pump, air-dried after being squeezed through a grease gun, and broken into lumps. It contained some 15% of sulphate ions, probably as a basic sulphate.

Batch D, lepidocrocite, was prepared by Baudisch and Hartung's method.[5] Ferrous chloride was first converted into the more stable tetrapyridineferrous chloride, which was then dissolved to a concentration of 20 g. per l. in 10 l. of distilled water. Oxygen was bubbled through the solution rapidly for 15 min. and more slowly for an additional 30 min., lepidocrocite then being slowly precipitated. It was filtered at the pump, washed several times on the filter, and transferred to a 1 l. beaker, which was then filled with distilled water. Excessive peptisation ensued, and so the mixture was left for two weeks, some recoagulation occurring; the supernatant liquid then gave no reaction for chloride ions, so the precipitate was filtered off at the pump and dried at 25°. This batch, unlike the other three, was in the form of a fine powder.

Procedure.—The thermogravimetric analysis was carried out in air, on the thermal balance,[6] the rate of rise of temperature being 200° per hr. For the extensometric examination the same rate of rise was usually employed, the accompanying change in length (and therefore in volume) of a compact of the original material being followed. The extensometer (Fig. 1*b*), of simple design, had been constructed by R. C. Asher.[7] The compact was placed at *S*, and the change in length was measured by observing through a cathetometer the difference in height between the indicator rod *I* and the reference rod *F*. The compact was made by adding a little distilled water to the crushed material and compressing it with a standard force (usually 4000 lb.) in a die with a ramrod (3/8" in diameter). The compact being assumed to shrink isotropically, its volume v_T at any temperature T is calculated from its length l_T as $v_T = (\pi/4)(d/l)^3 l_T^3$, where d and l are respectively the diameter and length of the compact at the end of the experiment.

For the preparation of a member of the calcination series at a temperature T_c, say, about 10 g. of the starting material were placed in the furnace of a thermal balance, heated to T_c during a definite period ($\frac{1}{2}$ hr.), and kept at T_c for 5 hr. It was then removed from the furnace and separate portions of it were used for (*a*) volumetric sorption [16] of nitrogen at −185° for

[1] Gregg and Packer, *J.*, 1955, 51.
[2] Gregg and Wheatley, *J.*, 1955, 3804.
[4] Hill, Ph.D. Thesis, London University, 1950.
[5] Baudisch and Hartung, "Inorganic Syntheses," 1939, **1**, 184.
[6] Gregg and Winsor, *Analyst*, 1954, **70**, 336.
[7] Asher, Ph.D. Thesis, London, 1955.

calculation of the specific surface, (*b*) determination of the density by immersion [9] in water or in carbon tetrachloride, (*c*) measurement of the lump volume by immersion in mercury, (*d*) gravimetric determination [8] of the sorption isotherm of water, methanol, or carbon tetrachloride, (*e*) *X*-ray analysis, and (*f*) electron-microscopic examination (batch D only). The volatile matter content was obtained from a separate sample of the starting material by repeating the preparation procedure at T_c then raising the temperature to 1000° in the thermal balance.

For determination of lump volume, about 1 g. of solid was weighed into the bulb *A* (Fig. 1*a*), which was attached to the tap unit *B*, and the whole container *D* was weighed before and after out-gassing at 100°. Freshly distilled mercury was then admitted through *C* and *B* till the level was above *B*, and after an hour (to allow penetration under 1 atm. pressure) *B* was closed, the excess of mercury removed, and *D* again weighed. The lump volume v_L (*i.e.*, the volume of the space per g. of Fe_2O_3, not penetrated by the mercury) is then given by $v_L = (1 + w)(v_B - W_2/\rho_T)W_1$, where v_B is the volume of the container *E* (*i.e.*, to tap *B*), W_1 the weight of outgassed solid, W_2 the weight of mercury in *E*, ρ_T the density of mercury at the temperature of experiment, and w the content of volatile matter per g. of Fe_2O_3. In order that the mercury shall surround the grains of solid completely they must not be finer [10] than 70 μ; the gel lumps

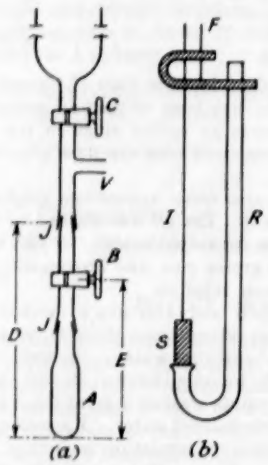


FIG. 1. (*a*) *Determination of lump volume.* *A*, sample bulb; *B*, *C*, taps; *J*, *J*, B-10 joints; *V*, to tap and high vacuum. (For *D* and *E* see text.)

(*b*) *Extensometer.* *F*, reference rod; *I*, indicator rod; *R*, supporting rod; *S*, compact. (*F*, *I*, nichrome; *R*, "Brightray S" alloy.)

of batches A, B, and C were well above this size, but no measurements were made on batch D because the particles were much too fine.

The lump volume thus measured is then the volume of the solid plus the volume of all the pores below 50,000 Å in radius, because mercury cannot enter any finer pores when the pressure across the meniscus is 1 atm.

The *X*-ray examination of batches B and C was kindly arranged for by Mr. J. T. Richmond (of Laporte Titanium Ltd.) and of batch D by Mr. J. H. Harwood (of Peter Spence and Co.), the electron micrographs being kindly taken by Miss D. L. Tilleard with a magnification of 5000 diameters.

The specific surface (*S*) is usually expressed as the number of square m. per g. of the outgassed sample, and this is a suitable measure of the absorbing power for practical purposes. Two other measures of the surface area are of value, however, in discussing the opposing processes of the loss of surface by sintering and the development of new surface in an active solid produced by calcination of a parent solid with evolution of a gaseous product; these are *S'*, the area per g. of non-volatile material, and *S''*, the area per cm.³ of the outgassed sample. The first, given simply by $S' = S(1 + w)$, shows by its variation along the calcination series the way in which one and the same sample of gel (having an Fe_2O_3 content of 1 g.) would change in area when heated for 5 hr. at each temperature, if the effect of all previous heating could be ignored.

[8] Gregg, *J.*, 1955, **1438**.
[9] Cf. Culbertson and Dunbar, *J. Amer. Chem. Soc.*, 1937, **59**, 306.
[10] Shapiro and Kolthoff, *J. Phys. Colloid Chem.*, 1948, **52**, 1020.

The second, given by $S'' = S\rho$, is merely the ratio of the surface to the true volume of the material. (Here ρ is the true density, *i.e.*, nearly the density by immersion in water or carbon tetrachloride.)

Results and Discussion

According to the views expressed in Part I,[11] a hydrous oxide should not develop an increased surface (*i.e.*, become "activated") on being heated but should show a continuous loss of surface—through sintering—as the temperature progressively rises; but with a hydrate or hydroxide which undergoes a change of lattice structure when the volatile product is driven off by heat, an activation is expected to result from this change—if it is drastic enough—followed as the temperature increases by a sintering of the same kind as for the hydrous oxide; a maximum in the curve of specific surface plotted against temperature of calcination would thus be produced. The results of the present work substantially confirm these views, and they indicate that the decomposition of lepidocrocite is a special case in that, although a lattice change occurs, it is too slight to necessitate recrystallisation, so that the increase in specific surface is small. They also indicate that upwards from some temperature near the Tammann point, the movement of ions through the bulk of material plays a rapidly increasing part in the mechanism of sintering.

Batch D.—It will be convenient first to discuss the results for batch D (lepidocrocite). In the curve for thermogravimetric analysis (T.G.A.) (Fig. 2), the composition at the inflection F, near 250°, is close to that required by the formula FeO·OH; the fall between E and F (cf. the first peak in the derived curve, II) corresponds to the loss of absorbed water, and the further fall between F and G (cf. second peak in I) to the chemical decomposition. The T.G.A. curve is in broad agreement with the curve for volatile-matter content (Fig. 3), though as each point now corresponds to the static conditions of a fixed, in contrast to the dynamic conditions of a rising, temperature the fall naturally occurs at a somewhat lower temperature. The reality of the decomposition is confirmed by the X-ray photographs for the samples of the calcination series (Plate 1): the original material and the sample corresponding to 150° both show the pattern of lepidocrocite, that for 200° is very indistinct but gives faint indication of α-Fe_2O_3, whereas for all higher temperatures the pattern is exclusively that of α-Fe_2O_3.

At first sight the chemical decomposition might, as already indicated, be expected to lead to a marked increase in surface. In actual fact, however, the rise in S (Fig. 4) and in S'' was relatively small, and, most strikingly, the surface S' per gram of Fe_2O_3 scarcely changed at all; the actual ratios were $S_2/S_1 = 1{\cdot}115$, $S_2''/S_1'' = 1{\cdot}425$, and $S_2'/S_1' = 1{\cdot}01$ (suffix 2 refers to 250° and suffix 1 to 150°). These results are readily explained if the crystallites of lepidocrocite are plates (*i.e.*, with negligible area of side faces) which on decomposition merely shrink in a direction perpendicular, but not parallel, to the plane of such plates; for then $S_2'/S_1' = 1{\cdot}0$ and (on insertion of the appropriate values of ρ and w in the conversion formulæ for S'' and S—see p. 3614) $S_2/S_1 = 1{\cdot}105$ and $S_2''/S_1'' = 1{\cdot}415$, close to the experimental values. Any model in which approximately isodimensional particles shrink equally in all directions would give ratios divergent from the experimental data; cubic crystallites, for example, give $S_2'/S_1' = 0{\cdot}80$, $S_2/S_1 = 0{\cdot}87$, and $S_2''/S_1'' = 1{\cdot}12$; to keep S' constant it would be necessary for exactly the correct proportion of particles to split up in such a manner as to give an additional 25% of area as compared with non-splitting (*e.g.*, by 75% of the cubes splitting parallel to one face). The plate model does not involve an arbitrary occurrence of this kind and would seem more plausible inasmuch as the lattice of lepidocrocite is layer-like. The electron micrographs too are not incompatible with the model: the finest spots could be individual plate-like particles, and the larger ones aggregates of these particles (Plate 2). To account for the experimental value of S'' the thickness of the plates would have to be $\tau = 2/(300 \times 10^4)$ cm., *i.e.*, *ca.* 67 Å for the 25° sample, with a diameter at least tenfold greater if they are to act as plates. The finest particles in the photographs are of the correct order of size to represent side or end faces of such plates.

A simple shrinkage of the kind envisaged could only occur if the difference in the lattices of the parent substances and of the final product is small enough; and since in both lattices

[11] Gregg, *J.*, 1953, 3940.

the ferric ions are in octahedral co-ordination [13] with the oxygen ions, the elimination of water between the hydroxyl groups of neighbouring layers of lepidocrocite need not destroy the arrangement.

FIG. 2.

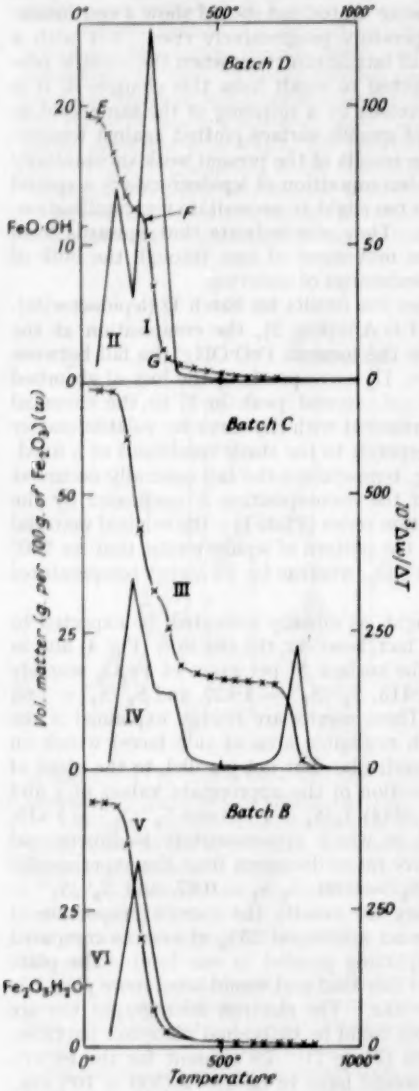
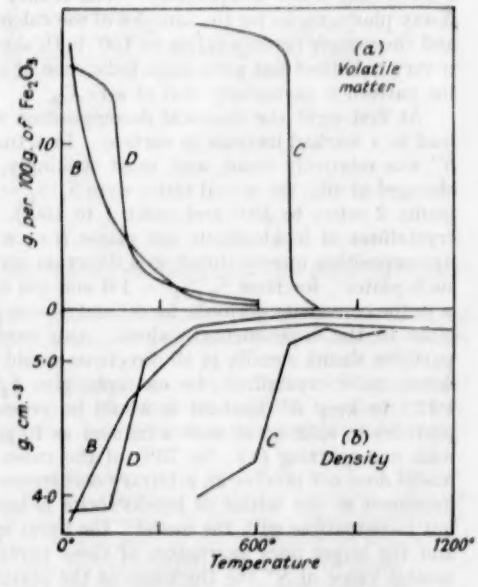


FIG. 2. *Thermogravimetric analysis.*
Curves I, III, V, plot of content of volatile matter (w) per 100 g. of Fe_2O_3 against temperature of calcination T.
Curves II, IV, VI, plot of $\Delta w/\Delta T$ against T.

FIG. 3. (*a*) *Plot of volatile-matter content against temperature of calcination.*
(*b*) *Plot of density against temperature of calcination.*
(The batch is marked on each curve. In Fig. 3*b* the density was by immersion in water for *B* and *C*, and in carbon tetrachloride for *D*.)

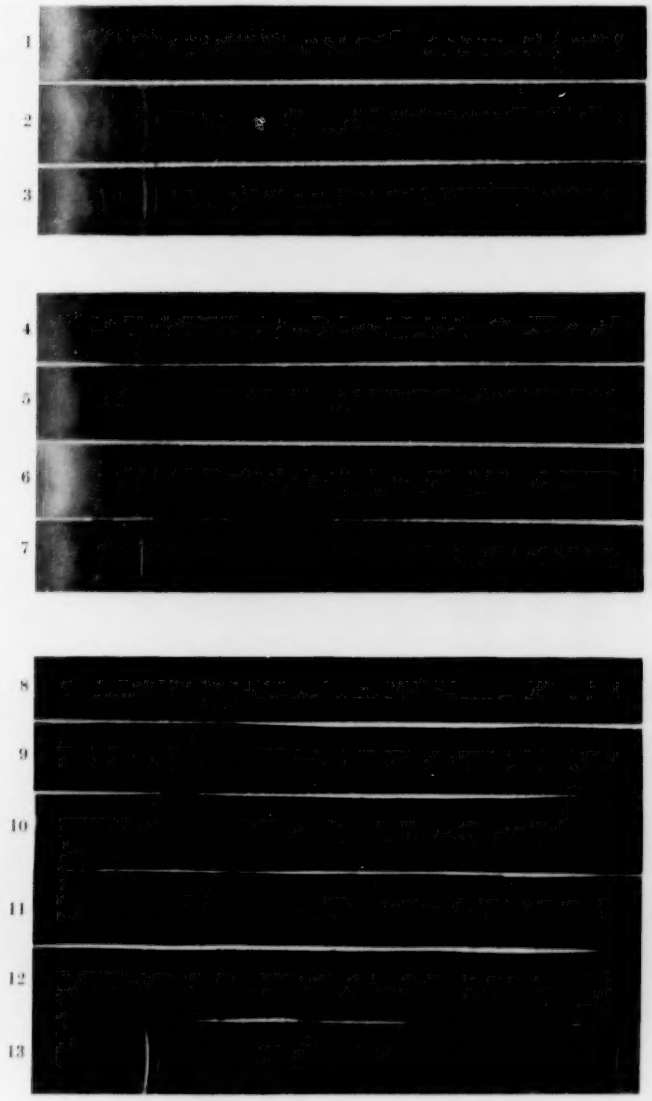
FIG. 3.



As the calcination temperature progressively rises above 250° the surface diminishes in the manner usual for many active solids, indicating some kind of sintering process. As is seen from the plot of log S'' against the temperature of calcination (Fig. 5), the rate of fall becomes much greater above 600°, and reference to the electron micrographs indicates a reason: between 600° and 800° the proportion of medium-sized and large particles grows at the expense of the very small ones, and in the 1000° and 1100° samples the effect is much

PLATE 1.

X-Ray diagrams for batches B, C, and D heated for 5 hours at the temperature stated.

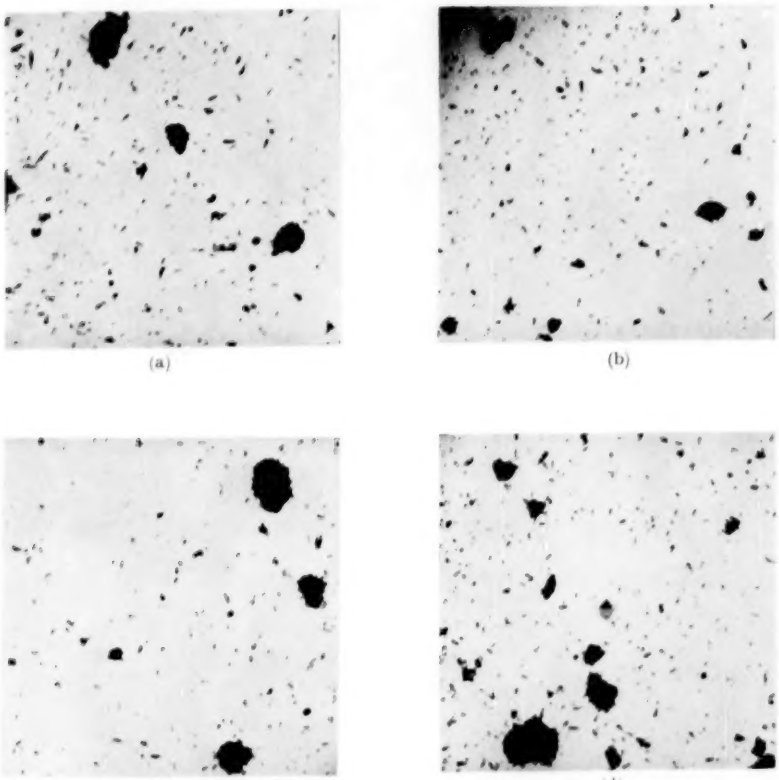


Batch B : (1) original material, (2) 600°, (3) 1000°.
Batch C : (4) original material, (5) 600°; (6) 700°; (7) 900°.
Batch D : (8) original material, (9) 150°, (10) 200°, (11) 250°, (12) 400°, (13) 1000°.

(*To face p. 3616.*)

PLATE 2

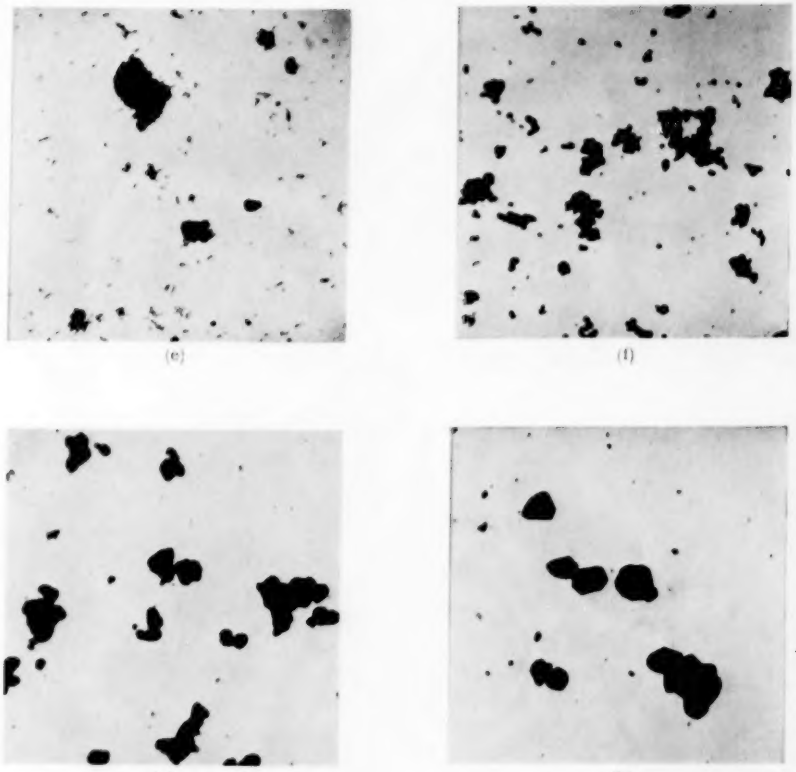
Electron micrographs of batch D (lepidocrocite) after calcining at various temperatures for 5 hours.



(a) (b) (c) (d)

Calcination temperatures : (a) original material, (b) 150°, (c) 250°, (d) 400°.
2·5 cm. = 10μ

PLATE 2 (*contd.*).



(e) (f)

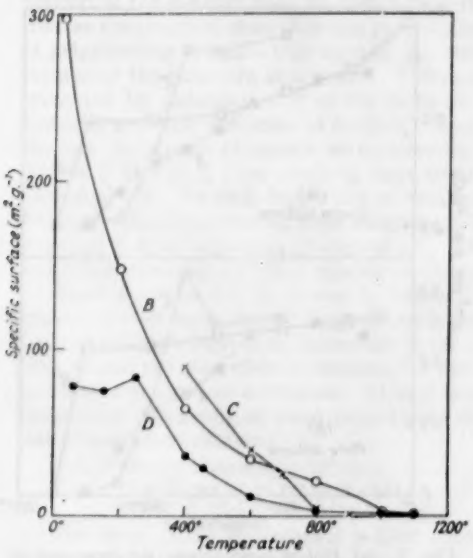
(g) (h)

Calcination temperatures: (e) 600°, (f) 800°, (g) 1000°, (h) 1100°.
2·5 cm. = 10μ
(By courtesy of Miss D. L. Tilleard and Paint Research Station.)

accentuated. The rapid reduction in surface setting in above 600° is therefore attributable to an actual union of the individual grains—a process which is able to occur because the Tammann temperature is now probably exceeded so that migration of ions between contiguous particles can occur.

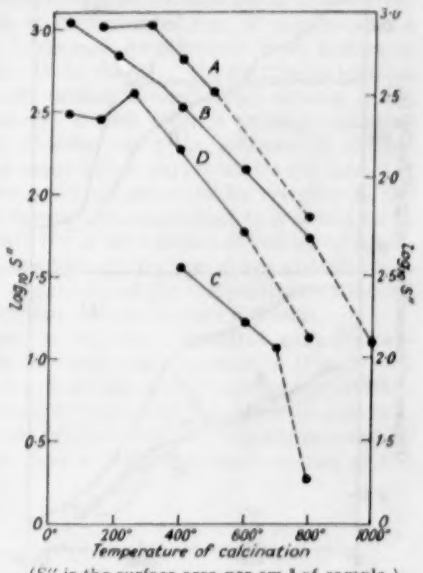
The disappearance of surface *below* 600° (Figs. 4 and 5) must be caused by the progressive annihilation of the internal rather than the external surface, *i.e.*, it arises from the closing of fine pores and channels within the grains. Reference to the adsorption isotherms [12] (not shown) bears this out: those of water show a hysteresis loop for temperatures up to 400° but not for 600°, and those of carbon tetrachloride a loop for 250° but not for 400°;

FIG. 4. *Plot of specific surface (by sorption of nitrogen at −183°) against temperature of calcination.*



(The batch is marked on each curve.)

FIG. 5. *Plot of* $\log_{10} S''$ *against temperature of calcination.*



(S'' is the surface area per cm.³ of sample.)

(The batch is marked on each curve.)

Curves *B* and *D*, left-hand scale.
Curves *A* and *C*, right-hand upper and lower scales respectively.

thus any pores wide enough to accommodate carbon tetrachloride molecules have disappeared by 250° and any wide enough for water molecules by 400°. The *mechanism* of this low-temperature loss of surface will be considered later.

Batch C.—The main point of interest in the results for batch C relates to the loss of sulphate ions (mainly as sulphur trioxide) at high temperature. The T.G.A. derived curve (Fig. 2, Batch C) shows two main peaks, at *ca.* 200° and 800° respectively, with a subsidiary one at 350°; the first is clearly due to loss of adsorbed water, and the second of sulphur oxides, the third being unexplained but possibly due to loss of water of hydration from the basic sulphate. The curve of volatile-matter content against temperature (Fig. 3*a*) which corresponds to static conditions shows that the loss is almost complete at 700°, a temperature lower, naturally, than for the dynamic conditions of Fig. 2C. Correspondingly the density has risen, by 700°, to a value near that of α-Fe_2O_3.

Now, it is very curious that this quite drastic occurrence—the loss of nearly 15% by weight of volatile material—should produce scarcely any effect on either the lump volume

[12] Goodman, Ph.D. Thesis, London University, 1955, pp. 63 *et seq.*
[13] Wells, "Structural Inorganic Chemistry," Oxford Univ. Press, 1950, 413, 423.

(Fig. 7*a*) or the surface area (the point for 700° in Fig. 5 lies quite well on the same straight line as those for 400° and 600°, and only for 800° is an acceleration of sintering apparent); yet the pore volume (Fig. 7*b*) increases markedly, by an amount, in fact, which is equivalent to the volume the volatile product would occupy in the fórm of solid sulphur trioxide with its normal density. (Increase in pore volume, 0·084 cm.^{3}; volume of lost SO_3 calc. as solid, 0·081 cm.^{3}; both per g. of Fe_2O_3.)

It is thus clear that the holes left by the expelled sulphur trioxide cannot remain in the interior, but must move to the exterior, of the micelles, and there merge with the intermicellar pores, thus contributing to the measured pore volume without adding to the

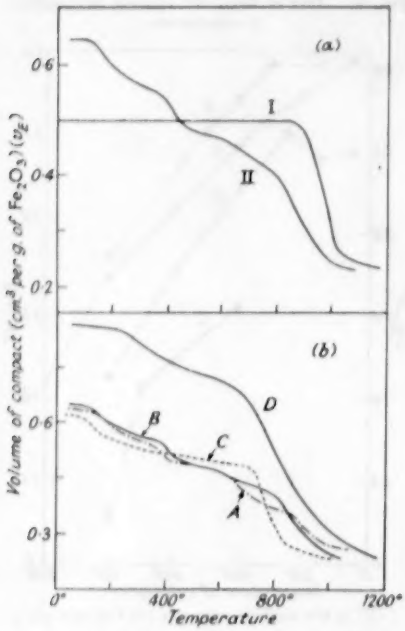


FIG. 6. *Extensometric examination. Plot of v_E against temperature of calcination.*

(*a*) I, the compact had been heated previously to 950°, then cooled before the run was commenced.

II, the compact was raised by 200° per hour without pre-treatment.

(*b*) Curves for batches A, B, C, D (as marked on the curve) with temperature rising by 200° per hour.

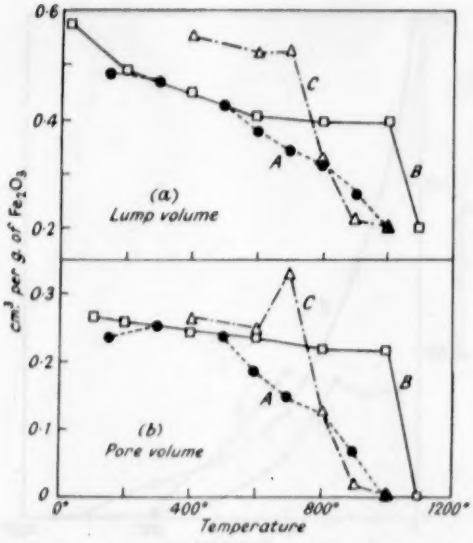


FIG. 7. (*a*) *Plot of lump volume (by immersion in mercury) against temperature of calcination.*

(*b*) *Plot of pore volume (calculated from lump volume and density in water or CCl_4) against temperature of calcination.*

(The batch is marked on each curve.)

specific surface. The constancy of the lump volume is accounted for if a framework structure is postulated, for this could remain intact despite changes *within* its constituent units (the micelles) provided the main intermicellar bridges were unaffected.

Incidentally, it is probably no accident that the loss of sulphur oxides first occurred at a temperature (700°) near the Tammann temperature of Fe_2O_3 (and presumably near that of the basic sulphate also); for in a basic sulphate the sulphate ions comprise only a portion of the anions and so could not occupy adjacent positions in the lattice. They could therefore not escape to the exterior by a place-exchange mechanism, but would have to wait until the remaining ions of the lattice became mobile. A mobility of this kind is also indicated by the coalescence of the sulphur trioxide vacancies already referred to.

By 800° there are signs of a general collapse of the framework: the surface area

decreases more rapidly (Figs. 4 and 5), the lump volume falls sharply (Fig. 7*a*), and the compact in the extensometer shows a marked contraction (Fig. 6). That the collapse did not occur at 700° when the sulphur trioxide was expelled is somewhat surprising; and a possible explanation is that the large shrinkage which occurs in each micelle when the gas is expelled (cf. Fig. 3*b*) breaks many of the subsidiary junctions of the framework and weakens others so that the area over which intermicellar migration can occur is greatly reduced. It may also be significant that the content of sulphur trioxide still retained at 700° is sufficient to cover an area equal to that of the whole surface of the sample (if each SO_3 molecule covers 24 Å^2 the area of all the SO_3 molecules is 24·0 m.^{2}, cf. area of sample 22·9 m.^{2}, per g. of Fe_2O_3); its presence on the micellar surfaces could hinder the migration of ferric and oxygen ions, until it is driven off at 800° upwards.

The reduction in surface (Figs. 4 and 5) which accompanies an increase in temperature of calcination in the range below 700° still needs to be accounted for; it requires that a portion of the micelles shall be held within the framework by relatively weak bridges so that as temperature rises they can progressively "shake down": the contiguous surfaces of neighbouring micelles join up and the common surface is annihilated without a disruption of the structure as a whole. The mechanism of such union is probably adhesion promoted by deformation [14] of the participant micelles under the influence of surface forces at and near the areas of contact. Such a suggestion is supported by the fact that the rate of decrease of surface with increasing temperature, measured by the slope of the line for C in Fig. 5, is so small—a mere 0·0016 degree^{-1}, corresponding to a reduction in surface of 0·3% for each degree rise in temperature (for a fixed period of heating of 5 hr.). The rate-controlling process must accordingly be one having very low energy of activation, if indeed it is an activated process at all. The magnitude of the temperature coefficient is perhaps more suggestive of rigidity or viscosity than of, *e.g.*, surface diffusion.

Batch B.—The T.G.A. curves for batch B are, as expected, consistent with the progressive loss of water from a hydrous oxide, with no chemical decomposition (Fig. 2; *B*). Correspondingly, there is no maximum in the curve of specific surface against temperature (Fig. 4) and the only effect of increased temperature is to enhance the degree of sintering, and not to produce an activation. It is of interest, however, that the original material on progressive outgassing at room temperature does show a slight increase in surface as the water content diminishes:

Time of outgassing at 22° (hr.)	1·5	5	20
Volatile matter (g. per g. of Fe_2O_3)	0·182	0·156	0·140
Surface S' (m.^{2} per g. of Fe_2O_3)	337	343	367

The most likely explanation is that adsorbed water present in very narrow spaces between neighbouring micelles is being progressively removed, so that the walls of the spaces are added to the measured surfaces.

The actual course of the reduction in surface area with increase in temperature broadly resembles that for batches C and D, and also for batch A:[1] following the gradual fall in the low-temperature range, there is a much sharper fall at the high-temperature end (Fig. 5) denoting a collapse of the gel framework; but with batch B this sets in near and possibly above 800°, in contrast to batch C (700—800°), batch A (500—800°), and also to batch D where the coalescence of grains commences at 600—800°. Each of these ranges includes or is near to the Tammann temperature, but it would seem that second-order effects may supervene to cause a variation in the actual temperature of collapse or of coalescence according to the mode of preparation of the material.

The lump volume is especially interesting in this connection (Fig. 7*a*, curve *B*), indicating as it does a persistence of the framework structure to a temperature (1000°) some 300° above the Tammann temperature, and then a rapid collapse so that at 1100° the lump volume only slightly exceeds the true volume itself. That the relatively rapid heating during the preparation of the sample is an important factor is apparent from a comparison of the results of two experiments (curves I and II of Fig. 6*a*) with the extensometer. For curve I the compact was prepared at 25° in the usual manner but was then raised to 950°

[14] Bangham, *Trans. Soc. Glass Tech.*, 1947, **31**, 264.
[15] Gregg and Stephens, *J.*, 1953, 3951.

during ½ hr. in the thermal balance, and maintained at 950° for 5 hr., exactly as in preparing a sample of the calcination series; after cooling to 25° it was examined extensometrically with a temperature rising at 100° per hr. For curve II, the compact, prepared at 25°, was merely placed in the extensometer and raised by 200° per hr. in the usual way. The delayed collapse in I is quite clear. It seems that the rapid pre-heating with its corresponding rapid shrinkage (cf. the large increase in density, Fig. 3*b*) leads to a complete rupture of the weaker bridges of the framework and a partial rupture of many of the others; thus, though the framework still persists the transfer of ions across the bridges is slowed down.

The difference between the lump volume curves for batch B and batch A is remarkable in view of their very small difference in chloride content (A 0·04, B 0·15%). Yet when one recalls the extreme sensitivity of the properties of the electrical double layer to the concentration of the counter-ions in solution, it becomes clear that very small changes in such concentrations could profoundly affect the intermicellar forces and thus the structure of the gel when the sol particles join up.

Chemisorbed Water.—Attention has been drawn in earlier Parts [1,2] to the fact that in the preparation of active solids a small content of volatile matter persists until very high temperatures are reached; *e.g.*, with batch B 0·3% was still present at 600°. "Water" held at such high temperatures must be chemically sorbed, and since its quantity is of the order required to form a monolayer it probably exists as hydroxyl groups on the surface of the micelles. The values of the fraction θ of the surface thus covered are given in the

Temp. of calcination	Batch B		Batch D		Temp. of calcination	Batch B		Batch D	
	S'	θ	S'	θ		S'	θ	S'	θ
25°	343	1·6	89·2	1·2	400°	64·2	0·5	35·5	1·7
150	—	—	83·6	0·7	450°	—	—	24·0	1·8
200	153	0·9	—	—	600	33·7	0·5	11·2	2·2
250	—	—	84·3	1·4	800	10·2	0·3	—	—

S' = surface area per g. of Fe_2O_3.
θ = fraction of surface covered with chemisorbed water.

Table for batches B and D, calculated on the assumption that a molecule of chemisorbed water occupies 15 Å². (For temperatures up to 200° the area 10 Å² is used, corresponding to physical adsorption.) The values in excess of unity for batch D at the high temperatures could imply that a proportion of the hydroxyl groups are located on the surface of cracks too narrow to admit nitrogen, though if this were so the inaccessible area would have to be almost as large as the measured area itself.

If the "chemisorption" hypothesis is correct it means that the anion part of the surface is heterogeneous—part O^{2-} and part OH^-—from 200° or so up to 600° and probably beyond.

Conclusion.—The results of this study confirm the conclusion of Part II that the loss of water from a hydrous gel on calcination does not bring about an activation but only results in progressive deactivation. With the hydroxide lepidocrocite the thermal decomposition results merely in a shrinkage in thickness of the plate-like particles with comparatively small change in lattice structure; the corresponding activation is accordingly very slight. In the sulphate gel the expulsion of the sulphur trioxide again produces no activation, for the SO_3 vacancies merely migrate to the surface of the micelles and coalesce there, producing no increase in specific surface. In the two gels the framework is remarkably persistent and only breaks down at temperatures above (for one gel well above) the Tammann temperature; and only above this temperature do the discrete grains of lepidocrocite begin to coalesce.

Our thanks are offered to Mr. J. T. Richmond and Mr. J. H. Harwood and to the staffs of Laporte Titanium Ltd. and of Peter Spence and Co. for the *X*-ray analysis; to Dr. L. A. Jordan and Miss D. L. Tilleard of the Paint Research Station for the electron micrographs; to the I.C.I. Research Fund for apparatus; and to the Department of Scientific and Industrial Research for a maintenance grant for one of us (J. F. G.). Responsibility for conclusions drawn from the photographs is ours alone.

WASHINGTON SINGER LABORATORIES,
THE UNIVERSITY, EXETER.

[*Received, April 9th,* 1956.]

697. *Physical Properties and Chemical Constitution. Part XXV.** (a) *Determination of the Orientation Polarization of Alkylpyridines in Benzene Solutions by Two Independent Methods.* (b) *Dipole Moments of Alkylpyridines.*

By C. W. N. Cumper, A. I. Vogel, and S. Walker.

(*a*) The orientation polarizations of twenty-two alkylpyridines have been calculated from measurements of the dielectric constants and densities of their solutions in benzene. These values are compared with Smith's and Palit's modifications of Guggenheim's method of computing the orientation polarization from the dielectric constants and refractive indices of their solutions. The results obtained agree within the experimental errors for the systems studied.

(*b*) The dipole moments of twenty-two mono- and di-alkylpyridines in benzene solution are reported. The change in moment when the hydrogen atoms in position 2, 3, and 4 are replaced by various alkyl groups have been calculated and shown to be consistent with the relative values of the π electron densities computed for the different carbon atoms in pyridine. The moments of substituents in position 4 have been analysed quantitatively in terms of primary and induced bond moments. Finally the moments of five lutidines are compared with values derived from those for the picolines.

(a) *Orientation Polarizations.*

The dipole moment of a solute in a non-polar solvent is generally obtained from experimental measurements of the dielectric constants and densities of a series of dilute solutions; solute–solute interactions are eliminated by extrapolating the results to infinite dilution in the deduction of the molecular polarization ($_\infty P_2$). Guggenheim [1] has demonstrated that, provided the refractive indices of the solutions are measured, accurate densities of the solutions are not required; Smith [2] has further shown that all density data of the solutions may be dispensed with in the evaluation of dipole moments (cf. also Palit [3]). Comparison of the results obtained by the " density " and the " refractive index " method is available only for a small number of compounds. In this communication the orientation polarizations (P_o) obtained by both procedures for alkylpyridines in benzene are presented and discussed. The dipole moments of these compounds will be considered in Section (b).

Experimental

Apparatus.—The dielectric constants were obtained by the heterodyne-beat method using a circuit modified from that described by Smyth.[4] The main difference was the use of a cathode-ray tube instead of a " magic eye " as the indicating device for the balance point. The amplifer output was connected to the horizontal plates of the cathode-ray tube whilst the output of a tuning fork maintained by a 1000 cycles/sec. valve (Muirhead, type D-630-C) was connected to the vertical plates. The oscillator, controlled by a quartz crystal, operated at a frequency of 5×10^5 cycles/sec. The dielectric-constant cell and precision variable condenser were connected in parallel. A small copper-wire link (dipping into mercury cups mounted in Perspex blocks to eliminate interference from the condensation of moisture) in the high-tension lead to the cell enabled it to be switched in and out of the circuit. The position of the link was such that no change was detected on the cathode-ray tube when the link was removed and then replaced in the circuit. The link was close to the cell so that the capacity of the leads, etc., was reduced to *ca.* one-twentieth of the capacity of the cell filled with air.

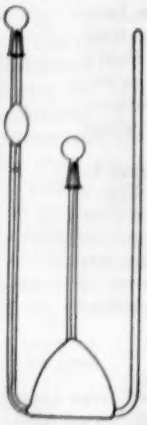
The factor limiting the accuracy was the Sullivan precision variable air-condenser (type No. C700 of 400 $\mu\mu$F capacity), which was the best available for use with a cell of capacity

* Part XXIV, *J.*, 1952, 514.

[1] Guggenheim, *Trans. Faraday Soc.*, 1949, **45**, 714.
[2] Smith, *ibid.*, 1950, **46**, 394.
[3] Palit, *J. Amer. Chem. Soc.*, 1952, **74**, 3952.
[4] Smyth, in Weissberger, " Physical Methods of Organic Chemistry," Interscience Publ. Inc., New York, 1949, Vol. I, p. 1638.

ca. 100 $\mu\mu$F when filled with air. An experienced operator, taking the mean of several readings, could obtain an accuracy of 1 part in 10,000—20,000 with the cell filled with air, and a somewhat better precision when it was filled with the solutions. An auxiliary variable condenser (of 400 $\mu\mu$F capacity) permitted the capacity of the cell to be measured over different regions of the standard condenser.

The dielectric-constant cell of Sayce–Briscoe type, as modified by Few, Smith, and Witten,[5] had a volume of *ca.* 16 ml. and an annulus 1 mm. wide. A 4 cm. gold guard-ring above the silvering on the inner surface of the outer cell wall eliminated both the "edge effect" and the interference from small variations in the water-level in the thermostat; the water-level was in fact kept constant.



The densities of the solutions were measured in a specially designed pyknometer (see Figure) provided with ground-glass caps on the side arms (bore 0·2 and 0·5 mm. respectively). The weight of solution filling the pyknometer (volume 10 ml.) was reproducible to 0·1 mg. or to 1 part in 10^5. All weights were corrected for buoyancy.

The refractive indices were measured on a Bellingham and Stanley refractometer of the Pulfrich type, reading to $\pm$0·00001.

Materials.—Thiophen-free "Catarex" reagent benzene (Petro-Chemicals Ltd.) was fractionated twice, dried over sodium wire, and partially frozen; the solid was melted and then redistilled in a fractional-distillation apparatus of 40 theoretical plates (Griffin and Tatlock Ltd., based on designs of the Anglo-Iranian Oil Company, Ltd.). The purified benzene was stored over sodium wire in an all-glass apparatus.

The alkylpyridines were prepared and purified by Mr. C. T. Kyte, B.Sc., of this Laboratory. Experimental details, together with other physical measurements on these compounds, are reserved for Part XXVI. Freshly distilled middle fractions were used throughout.

Procedure.—Six or eight solutions of each compound in benzene were used with weight fractions between 0·001 and 0·02. They were prepared in Pyrex glass-stoppered bottles which could be fitted with special delivery heads, with ground-glass joints, for transfer of the solution to the cell or pyknometer without exposure to the atmosphere.

Measurements were made in a large thermostat maintained at 25·00° $\pm$ 0·01°. The water was circulated through the refractometer by means of an efficient pump. The dielectric cell was calibrated with air and with pure benzene, and the pyknometer with benzene, both before and after each series of measurements.

Results.—The dielectric constants (ε_{12}), densities (d_{12}) and refractive indices (n_{12}) of the solutions of weight fractions w_2 are recorded in Table 1. In each case, over the concentration range studied, ε_{12}, d_{12}, and n_{12}^2 were linear functions of the weight fraction:

$$\varepsilon_{12} = \varepsilon_1(1 + \alpha w_2) \qquad d_{12} = d_1(1 + \beta w_2) \qquad n_{12}^2 = n_1^2(1 + \gamma w_2)$$

Calculation of results and discussion

To avoid giving undue weight to results in the most dilute solutions the values of α and β were calculated from the quotients:

$$\sum(\varepsilon_{12} - \varepsilon_1')/\sum w_2 = \alpha\varepsilon_1'; \ \sum(d_{12} - d_1')/\sum w_2 = \beta d_1'$$

where ε_1' and d_1' are the dielectric constant and density, respectively, of the solvent obtained by extrapolation of the experimental results to zero weight fraction. γ was obtained directly from a graphical plot. The orientation polarization (P_O) of the solute at infinite dilution was calculated from the values of α, β, and γ (Table 2) in two ways. In the following calculations ε_1 has been taken as 2·2725, d_1 as 0·87378 g. cm.$^{-3}$, and n_1 as 1·49790.

(i) *Orientation Polarization from α and β.*—The total molecular polarization at infinite dilution is given by the formula (cf. ref. 6, p. 55):

$${}_\infty P_2 = \frac{M_2}{d_1}\left[\frac{3\alpha\varepsilon_1}{(\varepsilon_1 + 2)^2} + \frac{\varepsilon_1 - 1}{\varepsilon_1 + 2}(1 - \beta)\right]$$

[5] Few, Smith, and Witten, *Trans. Faraday Soc.*, 1952, **48**, 211.
[6] Smith, "Electric Dipole Moments," Butterworths, London, 1955.

TABLE 1.

w_2	d_{12}	ε_{12}	n_{12}
Pyridine			
0·00183	0·87391	2·2861	1·49777
0·00378	0·87417	2·2975	1·49778
0·006398	0·87445	2·3160	1·49783
0·007889	0·87458	2·2358	1·49784
0·013451	0·87512	2·3633	1·49791
0·024696	0·87620	2·4397	1·49805
2-Methylpyridine			
0·00202	0·87394	2·2811	1·49781
0·00302	0·87398	2·2852	1·49782
0·006956	0·87425	2·3035	1·49786
0·009635	0·87441	2·3151	1·49790
0·014827	0·87473	2·3398	1·49794
0·017271	0·87487	2·3504	1·49795
0·020853	0·87512	2·3672	1·49798
3-Methylpyridine			
0·00222	0·87394	2·2890	1·49760
0·00410	0·87409	2·3009	1·49761
0·013548	0·87476	2·3645	1·49769
0·023013	0·87547	2·4282	1·49776
0·026266	0·87572	2·4490	1·49779
4-Methylpyridine			
0·00208	0·87381	2·2896	1·49764
0·00351	0·87409	2·3008	1·49770
0·007956	0·87428	2·3355	1·49771
0·015050	0·87471	2·3835	1·49777
0·021838	0·87515	2·4448	1·49781
0·026435	0·87545	2·4806	1·49786
4-Ethylpyridine			
0·00214	0·87391	2·2881	1·49771
0·00400	0·87401	2·3017	1·49774
0·00587	0·87414	2·3149	1·49772
0·011447	0·87446	2·3557	1·49775
0·016584	0·87477	2·3941	1·49778
0·020206	0·87499	2·4208	1·49780
2-n-Propylpyridine			
0·00160	0·87385	2·2773	1·49772
0·00298	0·87388	2·2815	1·49772
0·006972	0·87403	2·2943	1·49768
0·011823	0·87420	2·3098	1·49764
0·017090	0·87439	2·3272	1·49759
0·025336	0·87468	2·3539	1·49751
3-n-Propylpyridine			
0·00151	0·87384	2·2804	1·49766
0·00272	0·87395	2·2874	1·49767
0·00586	0·87405	2·3038	1·49763
0·012139	0·87436	2·3377	1·49760
0·019340	0·87469	2·3764	1·49758
0·022485	0·87486	2·3930	1·49756
4-n-Propylpyridine			
0·00139	0·87383	2·2816	1·49778
0·00240	0·87391	2·2891	1·49780
0·00529	0·87399	2·3065	1·49779
0·009154	0·87419	2·3318	1·49777
0·017327	0·87459	2·3855	1·49774
0·022906	0·87485	2·4214	1·49773
4-isoPropylpyridine			
0·00224	0·87387	2·2857	1·49777
0·00382	0·87393	2·2976	1·49775
0·007951	0·87411	2·3246	1·49770
0·013637	0·87434	2·3609	1·49767
0·017134	0·87449	2·3843	1·49765
0·030643	0·87506	2·4736	1·49753
2-n-Butylpyridine			
0·00177	0·87381	2·2771	1·49732
0·00319	0·87385	2·2810	1·49732
0·006023	0·87400	2·2891	1·49730
0·008827	0·87405	2·2927	1·49727
0·013819	0·87417	2·3113	1·49722
0·015575	0·87422	2·3158	1·49718
0·018588	0·87430	2·3267	1·49715
3-n-Butylpyridine			
0·00205	0·87385	2·2828	1·49787
0·00294	0·87389	2·2866	1·49784
0·00433	0·87393	2·2939	1·49782
0·008170	0·87408	2·3120	1·49780
0·012988	0·87428	2·3354	1·49777
0·015164	0·87436	2·3469	1·49778
0·017629	0·87446	2·3580	1·49775
4-n-Butylpyridine			
0·00177	0·87383	2·2836	1·49783
0·00356	0·87394	2·2941	1·49782
0·006127	0·87428	2·3086	1·49782
0·006779	0·87404	2·3122	1·49781
0·011302	0·87407	2·3397	1·49780
0·017345	0·87451	2·3758	1·49778
0·021843	0·87471	2·4014	1·49777
4-sec.-Butylpyridine			
0·00215	0·87387	2·2858	1·49788
0·00339	0·87395	2·2965	1·49785
0·006461	0·87406	2·3116	1·49785
0·010547	0·87424	2·3356	1·49782
0·010620	0·87425	2·3357	1·49781
0·015617	0·87445	2·3650	1·49778
4-tert.-Butylpyridine			
0·00206	0·87389	2·2846	1·49766
0·00406	0·87391	2·2965	1·49764
0·00571	—	2·3053	—
0·006718	0·87410	2·3126	1·49763
0·014916	0·87449	2·3535	1·49758
0·015554	—	2·3640	—
0·019529	0·87472	2·3886	1·49756
0·026427	0·87505	2·4302	1·49751
2-n-Pentylpyridine			
0·00203	0·87380	2·2783	1·49775
0·00328	0·87383	2·2810	1·49778
0·006180	0·87388	2·2886	1·49773
0·009279	0·87392	2·2961	1·49771
0·010395	0·87394	2·2992	1·49769
0·012189	0·87397	2·3028	1·49767
4-n-Pentylpyridine			
0·00170	0·87383	2·2808	1·49790
0·00369	0·87388	2·2918	1·49783
0·00683	0·87400	2·3085	1·49776
0·012615	0·87414	2·3389	1·49766
0·020317	0·87437	2·3800	1·49761
0·022570	0·87443	2·3910	1·49754
4-1′-Ethylpropylpyridine			
0·00195	0·87383	2·2820	—*
0·00386	0·87392	2·2926	—
0·00502	0·87394	2·3000	—
0·007437	0·87402	2·3139	—
0·014663	0·87426	2·3507	—
0·020696	0·87445	2·3855	—
2 : 3-Lutidine			
0·00203	0·87392	2·2834	1·49780
0·00254	0·87394	2·2862	1·49780
0·00621	0·87417	2·3035	1·49783
0·012719	0·87456	2·3352	1·49787
0·019032	0·87495	2·3666	1·49791
0·024004	0·87524	2·3908	1·49792
2 : 4-Lutidine			
0·00135	0·87382	2·2798	1·49775
0·00264	0·87389	2·2883	1·49775
0·00600	0·87402	2·3049	1·49776
0·011313	0·87427	2·3327	1·49778
0·016209	0·87448	2·3592	1·49770
0·021885	0·87424	2·3886	1·49776
2 : 5-Lutidine			
0·00187	0·87388	2·2811	1·49770
0·00385	0·87396	2·2902	1·49772
0·008380	0·87418	2·3107	1·49770
0·012816	0·87440	2·3318	1·49772
0·014327	0·87446	2·3391	1·49770
2 : 6-Lutidine			
0·00128	0·87381	2·2771	1·49782
0·00261	0·87387	2·2820	1·49775
0·007078	0·87404	2·2931	1·49772
0·009633	0·87412	2·3002	1·49770
0·014343	0·87429	2·3127	1·49769
0·020564	0·87454	2·3302	1·49767
3 : 5-Lutidine			
0·00177	0·87387	2·2855	1·49777
0·00241	0·87391	2·2888	1·49774
0·00683	0·87414	2·3176	1·49780
0·013609	0·87450	2·3638	1·49782
0·021144	0·87492	2·4136	1·49783
0·027560	0·87527	2·4578	1·49784

* The refractive indices of the solutions of 4-1′-ethylpropylpyridine were measured at different weight fractions from those used above. The values of w_2 and n_{12} respectively were: 0·00127, 1·49781; 0·00356, 1·49779; 0·00725, 1·49777; 0·009729, 1·49775; 0·016860, 1·49769; 0·021793, 1·49766.

Allowance for the electron and atom polarization was made by subtracting the molar refraction R_D, *i.e.*, $P_o = {}_\infty P_2 - R_D$.

In order to compare the results for P_O with those deduced by method (ii), we have preferred to use a value of R_D derived from the refractive indices and densities of the dilute solutions, rather than use the value for the pure solute. It was assumed that $r_{12} = w_1 r_1 + w_2 r_2$, or $\delta r_{12}/\delta w_2 = r_2 - r_1$, where the r's are the specific refractions. From the linear graph of r_{12} against w_2 the specific, and hence the molar, refraction of the solute was obtained. In some cases this value of R_D was slightly greater, but in others slightly smaller, than the value determined directly, the mean difference being 0·19 ± 0·11 cm.^{3}.

(ii) *Orientation Polarization from α and γ.*—In this method the orientation polarization is given (cf. ref. 2) by :

$$P_O = \frac{M_2}{d_1}\left[\frac{3\alpha\varepsilon_1}{(\varepsilon_1+2)^2} - \frac{3\gamma {n_1}^2}{({n_1}^2+2)^2}\right] + C$$
$$= P + C$$

where C is a small correction, seldom greater than unity, the value of which depends on the assumption made regarding the atom polarization. If the electron and atom polarizations are assumed to be equal to R_D, then Smith [2] (equation 10 on p. 398) finds that the value of C is given by the expression :

$$C\ (\text{Smith}) = \frac{M_2}{d_2}\left[\frac{\varepsilon_1 - 1}{\varepsilon_1 + 2} - \frac{{n_1}^2 - 1}{{n_1}^2 + 2}\right]$$

Palit [3] (equation 7, rearranged, on p. 3953) gives the expression

$$C\ (\text{Palit}) = \frac{M_2}{d_1}\left[\frac{\varepsilon_1 - 1}{\varepsilon_1 + 2} - \frac{{n_1}^2 - 1}{{n_1}^2 + 2}\right](1 - \beta)$$

If the rectilinear relation between d_{12} and w_2 held over the complete concentration range, then

$$d_2 = d_1(1 + \beta)$$

and

$$\frac{1}{d_2} = \frac{1}{d_1(1+\beta)} = \frac{(1-\beta)}{d_1(1-\beta^2)}$$

Normally β^2 is $\ll 1$, so the two expressions for C would be virtually identical. Dr. J. W. Smith (personal communication) has pointed out that his expression assumes that the specific volumes of the solutions (v_{12}) are a linear function of w_2 and, if the behaviour of the solutions is ideal, this linearity would hold up to $w_2 = 1$: hence,

$$v_2 = v_1 + \delta v/\delta w_2$$

and

$$\frac{1}{d_2} = \frac{1}{d_1} + \frac{\delta(1/d)}{\delta w_2} = \frac{1}{d_1} - \frac{1}{{d_1}^2}\left(\frac{\delta d}{\delta w_2}\right)_{w_2=0}$$
$$= \frac{1-\beta}{d_1}$$

i.e., the two expressions for C would be identical. A necessary condition for the accurate determination of dipole moments in solution is that the solutions should not depart greatly from ideal behaviour and in consequence the difference between C (Smith) and C (Palit) must be small. With the systems under investigation the extrapolated values of d_2 and v_2 differ by less than 1% from the experimental values and the two expressions for C [*i.e.*, C (Smith) and C (Palit)] give values which differ only by about 0·002 cm.^{3}.

The values calculated for C, ${}_\infty P_2$, and P, and the two values of P_O {$({}_\infty P_2 - R_D)$ and $(P + C)$} are recorded in Table 2. These values are quoted to 0·01 cm.^{3} solely for comparison : it is realised that the absolute values are not as accurate as this implies. It is evident that provided the factor C is included the results obtained for P_o by the

" density " and the " refractivity " method are in good agreement. The mean difference, including the sign, between the two values of P_o is actually 0·02 with a standard deviation of 0·05. If the values of R_D determined on the pure solute are used, as is normally done

TABLE 2.

Pyridine deriv.	α *	β	γ	C (cm.³)	R_D (cm.³)	$_\infty P_2$ (cm.³)	P (cm.³)	P_o (cm.³) $_\infty P_2 - R_D$	P_o (cm.³) $P + C$
Pyridine	$2{\cdot}965_4$	$0{\cdot}111_0$	$+0{\cdot}014_5$	0·38	24·17	124·23	99·75	100·06	100·13
2-Methyl	$1{\cdot}991_3$	$0{\cdot}071_0$	$+0{\cdot}012_3$	0·47	29·52	108·75	78·75	79·23	79·22
2-*n*-Propyl	$1{\cdot}416_9$	$0{\cdot}041_1$	$-0{\cdot}012_4$	0·63	38·31	112·99	74·03	74·68	74·64
2-*n*-Butyl	$1{\cdot}245_2$	$0{\cdot}031_7$	$-0{\cdot}013_6$	0·72	42·99	116·59	72·76	73·60	73·48
2-*n*-Pentyl	$1{\cdot}237_1$	$0{\cdot}017_2$	$-0{\cdot}016_1$	0·80	47·86	121·63	72·70	73·77	73·50
3-Methyl	$2{\cdot}962_4$	$0{\cdot}084_9$	$+0{\cdot}010_3$	0·46	29·04	146·99	117·51	117·95	117·97
3-*n*-Propyl	$2{\cdot}347_4$	$0{\cdot}055_9$	$-0{\cdot}005_8$	0·62	38·13	160·62	121·87	122·49	122·49
3-*n*-Butyl	$2{\cdot}127_7$	$0{\cdot}044_3$	$-0{\cdot}007_7$	0·70	42·76	167·00	123·43	124·24	124·13
4-Methyl	$3{\cdot}478_4$	$0{\cdot}073_1$	$+0{\cdot}010_0$	0·47	29·38	167·88	138·05	138·50	138·52
4-Ethyl	$3{\cdot}138_1$	$0{\cdot}068_4$	$+0{\cdot}006_0$	0·54	33·72	177·75	143·45	144·03	143·99
4-*n*-Propyl	$2{\cdot}862_9$	$0{\cdot}053_1$	$-0{\cdot}004_9$	0·62	38·24	187·39	148·53	149·15	149·15
4-*iso*Propyl	$2{\cdot}872_2$	$0{\cdot}047_6$	$-0{\cdot}010_9$	0·63	38·14	188·10	149·32	149·96	149·95
4-*n*-Butyl	$2{\cdot}597_4$	$0{\cdot}048_3$	$-0{\cdot}008_4$	0·70	42·74	193·95	150·58	151·21	151·28
4-*sec.*-Butyl ...	$2{\cdot}594_4$	$0{\cdot}050_1$	$-0{\cdot}009_9$	0·70	42·47	193·68	150·46	151·21	151·16
4-*tert.*-Butyl ...	$2{\cdot}624_3$	$0{\cdot}053_8$	$-0{\cdot}009_7$	0·70	42·32	195·26	152·21	152·94	152·91
4-*n*-Pentyl	$2{\cdot}340_3$	$0{\cdot}032_2$	$-0{\cdot}020_3$	0·78	47·14	198·47	150·56	151·33	151·34
4-1′-Ethyl-*n*-propyl	$2{\cdot}394_3$	$0{\cdot}037_4$	$-0{\cdot}009_5$	0·78	47·44	201·71	153·39	154·27	154·17
2 : 3-Lutidine ...	$2{\cdot}146_9$	$0{\cdot}069_7$	$+0{\cdot}008_4$	0·54	33·80	132·30	97·94	98·50	98·48
2 : 4-Lutidine ...	$2{\cdot}338_4$	$0{\cdot}050_3$	0·000	0·55	34·10	141·77	107·09	107·67	107·64
2 : 5-Lutidine ...	$2{\cdot}041_8$	$0{\cdot}054_3$	0·000	0·55	33·91	128·03	93·50	94·12	94·05
2 : 6-Lutidine ...	$1{\cdot}201_8$	$0{\cdot}041_6$	$-0{\cdot}008_3$	0·56	34·16	90·24	55·41	56·08	55·97
3 : 5-Lutidine ...	$2{\cdot}953_6$	$0{\cdot}061_4$	$+0{\cdot}002_3$	0·54	33·87	169·56	135·17	135·69	135·71

* The values of α have been quoted to the fourth decimal place solely to be able to express P_o to 0·01 cm.³. It is not intended to imply that they have an accuracy beyond the third decimal place.

in practice, this difference between the two values of P_o becomes 0·00 with a standard deviation of 0·24.

With benzene as solvent it is very unlikely that the factor C would be greater than unity for any solute. Consequently, in evaluating dipole moments by the " refractivity " method, C (and therefore d_2) need not be determined with great accuracy unless the solute has a low dipole moment (say, $<0{\cdot}7$ D). The densities of the solutions are not required in this method. With the compounds under investigation the factor C usually has a value less than 1% of P_O. Such a small value for C is only just significant in the determination of the dipole moment since the latter depends upon $\sqrt{(P_O T)}$. For $C = 0{\cdot}5$, P_O must fall to 30·32 cm.³ (corresponding to $\mu = 1{\cdot}22$ D) before the dipole moment is changed by 0·01 D.

We conclude that, for the compounds studied, the " density " and the " refractivity " method give equally accurate results for the orientation polarization of the solute in benzene solution.

(b) *Dipole Moments.*

For the accurate determination of the small differences in dipole moment in solution produced by substituents in a ring system, the dipole moment of the latter must be reasonably large. No comprehensive study of such a system has yet been made. The influence of alkyl groups in the pyridine system ($\mu = 2{\cdot}21$ D in benzene solution) is now discussed and in a future communication the investigation will be extended to other substituents.

RESULTS

The orientation polarizations (P_O) at 25·00° of alkylpyridines dissolved in benzene have been presented above. Their dipole moments (in Debye units) have been calculated from the usual formula $\mu = 0{\cdot}01281\sqrt{(P_O T)}$, where T is the absolute temperature, and are listed in Tables 3 and 5. Earlier values (where available) are also given. All the calculations in this paper have been carried out to the third decimal place in the dipole moment; the results are shown to 0·001 D only for the 4-alkylpyridines to demonstrate how closely an empirical equation can be made to agree with the measured dipole moments.

Apart from the theoretical limitations in evaluating dipole moments in solution the results are considered to be accurate to 0·01 D. (A variation of 0·01 D corresponds to a change in P_O of 0·86 cm.[3] for $\mu = ca.$ 1·90 D, and of 1·12 cm. for $\mu = ca.$ 2·74 D; this is also the order of magnitude of the atom polarizations in pyridine and in α- and β-picoline.[7]) If the distortion polarization is taken as $1{\cdot}05R_D$ instead of R_D then the moment of 4-methylpyridine is reduced by 0·011 D whilst that of 4-*n*-butylpyridine is reduced by 0·019 D. These changes would not affect the arguments presented in this paper.

Discussion

4-Alkylpyridines.—Substituents in position 4 will be considered first since any error in the bond angles of pyridine will not affect the discussion and also because the rotation of the alkyl groups is not restricted by the nitrogen atom. The dipole moment of an alkylpyridine may be expressed as:

$$\mu = \mu_{C_5H_5N} - \mu_{C\text{-}H} + \mu_R + I$$

where $\mu_{C_5H_5N}$ is the dipole moment of pyridine, $\mu_{C\text{-}H}$ the bond moment of hydrogen attached to the pyridine ring in position 4, μ_R the moment associated with the alkyl group itself, and I the small change in the moment induced in the pyridine ring when its hydrogen atom is replaced by the alkyl group R.

We find that μ_R can be expressed in terms of a primary moment and the moments this induces in the components of the side chain attached to its α-carbon atom. This primary moment we consider to be a consequence of the different states of hybridization of the carbon atoms in the ring and in the side chain, *i.e.*, to arise mainly from the bond linking the ring to the side chain. If the primary moment is "*a*" (irrespective of its origin) and the C–H moment in saturated aliphatic compounds is "*b*" then, since saturated paraffins have zero dipole moments, μ_R consists of the moment $(a - b)$ together with the moment this induces in the C_α–H bonds (μ_H) and in the other C–C bonds in the chain. We assume that the moment induced in successive C–C bonds decreases in a geometrical progression, with constant ratio "*x*." μ_H includes any moment arising through hyperconjugation. The moments associated with the alkyl groups are therefore:

$3\mu_H + (a - b)$	for $CH_3{\cdot}C_5H_4N$
$2\mu_H + (a - b)(1 + x + x^2)$	for $CH_3{\cdot}CH_2{\cdot}CH_2{\cdot}C_5H_4N$
$\mu_H + (a - b)(1 + 2x)$	for $(CH_3)_2CH{\cdot}C_5H_4N$, etc.

All of the induced moments are their components resolved in the direction of the C_5H_4N–C_α bond. The values of x will vary slightly for each C–C bond in the substituent because of their different orientations with respect to the ring, but as these induced moments fall off rapidly with increasing chain length it is permissible, as an approximation, to take a single value for x.

The following values were calculated from the experimental results:

$$(a - b) = 0{\cdot}528 \text{ D} \qquad \mu_{C\text{-}H} - I = 0{\cdot}483 \text{ D}$$
$$\mu_H = 0{\cdot}115 \text{ D} \qquad x = 0{\cdot}310$$

These were employed in calculating the figures in the last column of Table 3.

The agreement with the observed values supports the preceding interpretation of the results except for *sec.*-butyl- and 1′-ethyl-*n*-propyl-pyridine; in the last two cases the differences are probably due to restricted rotation of the terminal components of the substituent group which decreases their contributions to the moment below that calculated. The agreement for *iso*propyl- and *tert.*-butyl-pyridine indicates that the inductive effect of one methyl on another attached to the same carbon atom is very small.

[7] Cartwright and Errara, *Acta Physicochim. U.R.S.S.*, 1935, **3**, 649; *Proc. Roy. Soc.*, 1936, *A*, **154**, 138.

The moment induced in C_α–$C_\beta H_2$ $\{(a - b)x\}$ and in the C_α–H bonds (μ_H) of the side chain have definite values but a small change in $(a - b)$, together with compensating change in the values of x and of $(\mu_{C-H} - I)$, is possible without materially affecting the agreement between the observed and the calculated dipole moments. Since μ_H is small the assumption

TABLE 3. *Dipole moments* (D) *of alkylpyridines.*

Alkyl	2-Alkyl	3-Alkyl	4-Alkyl obs.	4-Alkyl calc.
(H)	2·21 [a]	2·21	2·21[b]	—
Me	1·97 †	2·40 ‡	2·60[b] ¶	2·60[b]
Et	—	—	2·65[b]	2·65[b]
Pr^n	1·91	2·45	2·70[b]	2·70[b]
Pr^i	—	—	2·70[b]	2·70[b]
Bu^n	1·90	2·47	2·72[c]	2·71[c]
Bu^s	—	—	2·72[c]	2·75[b]
Bu^t	—	—	2·73[d]	2·74[c]
n-C_5H_{11}	1·90	—	2·72[d]	2·72[d]
$CHEt_2$	—	—	2·74[d]	2·80[d]

Earlier values: [a] 2·20,[a] 2·23,[b] 2·26[c]; † 1·96,[d] 1·92,[e] 1·72[f]; ‡ 2·30[f]; ¶ 2·57,[e] 2·4.[g]

[a] Leis and Curran, *J. Amer. Chem. Soc.*, 1945, **67**, 79. [b] Goethals, *Rec. Trav. chim.*, 1935, **54**, 299. [c] Middleton and Partington, *Nature*, 1938, **141**, 516. [d] Rogers and Campbell, *J. Amer. Chem. Soc.*, 1953, **75**, 1209. [e] Freiser and Glowacki, *ibid.*, 1948, **70**, 2575. [f] Rau and Narayanaswamy, *Z. phys. Chem.*, 1934, *B*, **26**, 23. [g] Huckel and Salinger, *Ber.*, 1944, **77**, 810.

that each hydrogen atom contributes equally to any hyperconjugation effect is not serious, though there should probably be a small extra moment from hyperconjugation in methylpyridine.

The C–H moment is usually thought to be very sensitive to the hybridization of *s*- and *p*-orbitals in the carbon atom to which the hydrogen atom is attached: the C–H moments [6] suggested for the usual hybridizations are sp^3 (−0·30 D), sp^2 (0·40 D), and sp (1·05 D). If one *s*- and two *p*-type orbitals of the ring-carbon atoms in pyridine are hybridized, to give three bonds at the experimentally observed bond angles,[8] then the carbon orbitals forming bonds to the hydrogen atoms in positions 2, 3, and 4 in pyridine have the normalized wave functions (cf. ref. 9):

$$\psi_2 = 0{\cdot}531\psi_s + 0{\cdot}848\psi_p$$
$$\psi_3 = 0{\cdot}594\psi_s + 0{\cdot}805\psi_p$$
$$\psi_4 = 0{\cdot}601\psi_s + 0{\cdot}799\psi_p$$

and the moments of the corresponding C–H bonds, interpolated in terms of the amount of *s* character in the carbon atomic orbital, are $C_{(2)}$–H = 0·06 D, $C_{(3)}$–H = 0·50 D, and $C_{(4)}$–H = 0·54 D. From these figures b would have a value −0·30 D (sp^3 hybridization), and a would be 0·528 + 0·30 = 0·83 D. This is 0·29 D greater than the moment of the C–H bond in position 4 in pyridine (0·54 D) and is the cause of the extra moment (I) induced in the ring when this hydrogen atom is replaced by an alkyl group. The above figures give a value of 0·06 D for I.

2-, 3-, and 4-Alkylpyridines.—The increase in moment $\Delta\mu$ $(= -\mu_{C-H} + \mu_R + I)$ when a hydrogen atom in the pyridine ring is replaced by the alkyl group R has been calculated from the observed dipole moments by vector analysis. It is assumed that the resultant moment of the alkyl group acts in the direction of the original pyridine C–H bond and that the pyridine bond angles are as determined recently by Bak, Hansen, and Rastrup-Anderson [8] (*viz.*, $\angle NC_{(2)}C_{(3)} = 124° 00'$, $\angle C_{(2)}C_{(3)}C_{(4)} = 118° 36'$, $\angle C_{(3)}C_{(4)}C_{(5)} = 118° 06'$, $\angle NC_{(2)}H = 115° 44'$, and $\angle C_{(4)}C_{(3)}H = 121° 07'$).

The values of $\Delta\mu$ are collected in Table 4.

The most recent molecular-orbital calculations of π-electron densities at the carbon

[8] Bak, Hansen, and Rastrup-Anderson, *J. Chem. Phys.*, 1954, **22**, 2013.
[9] Coulson, "Valence," Oxford Univ. Press, 1952, p. 194.

atoms of pyridine [10] are included in Table 4. It will be noted that the $\Delta\mu$ values, an indication of the tendency of electronic charge to flow from the alkyl groups into the ring, are in the expected order. The exceptionally large values of $\Delta\mu$ for position 2 may be connected with the small polarity calculated above for the $C_{(2)}$–H bond in pyridine (0·06 D) and with the proximity of the highly electronegative nitrogen atom. The relative electron-density values are known to be in agreement with the chemical behaviour of pyridine.[11]

In addition to the values of $\Delta\mu$ in the various positions the individual values of $(a - b)$ and of μ_H would also be expected to depend inversely upon the electron densities at the carbon atoms. This is borne out by the differences between the $\Delta\mu$ values of *n*-propyl- and methyl-pyridines shown in Table 4.

TABLE 4. *Change in group moment* $\Delta\mu$ *when a hydrogen atom in pyridine is replaced by an alkyl group* R.

R	Position in ring 2 $\Delta\mu_2$	3 $\Delta\mu_3$	4 $\Delta\mu_4$	R	Position in ring 2 $\Delta\mu_2$	3 $\Delta\mu_3$	4 $\Delta\mu_4$
Me	0·56	0·36	0·39	Bu^t	—	—	0·52
Et	—	—	0·44	*n*-C_5H_{11}	0·83	—	0·51
Pr^n	0·80	0·44	0·49	$CHEt_2$	—	—	0·54
Pr^i	—	—	0·50	$\Delta\mu_{Py^+} - \Delta\mu_{Me}$	0·24	0·08	0·10
Bu^n	0·83	0·47	0·51	π Electron density in pyridine	0·939	0·988	0·945
Bu^s	—	—	0·51				

TABLE 5. *Dipole moments of lutidines* (D).

Lutidine	2 : 6-	2 : 5-	2 : 4-	2 : 3-	3 : 5-
μ (obs.)	1·66 *	2·15	2·30	2·20	2·58
μ (calc.)	1·61	2·09	2·35	2·23	2·55

* Earlier values: 1·65,[b] 1·87 [d] (for refs. *b* and *d* see Table 3).

Lutidines.—The lutidines were examined with a view to comparing their measured dipole moments with the values calculated by vector analysis from the observed moments of pyridine and the three methylpyridines; it was assumed that the geometries of pyridine and the picoline and the lutidine molecules are identical. The calculated dipole moments are included in Table 5 under μ (calc.).

The maximum difference between the calculated and the observed dipole moments is 0·06 D: a small departure from strict vector additivity would be expected in view of the above assumption and also because no account has been taken of the inductive effects round the ring.

The authors thank Imperial Chemical Industries Limited for a grant, and the Central Research Fund of the University of London for the loan of the Sullivan condenser.

WOOLWICH POLYTECHNIC, LONDON, S.E.18. [*Received, April 13th*, 1956.]

[10] Davies, *Trans. Faraday Soc.*, 1955, **51**, 449.
[11] Cf. Elderfield, "Heterocyclic Compounds," Wiley, New York, 1950, Vol. I, p. 546.

698. *The Kinetics of Alkyl–Oxygen Fission in Ester Hydrolysis. Part V.* Diphenylmethyl Esters in Aqueous Acetone.*

By G. J. Harvey and V. R. Stimson.

The kinetics of the acid-catalysed hydrolysis of diphenylmethyl 2 : 4 : 6-trimethylbenzoate, benzoate, acetate, and formate have been studied. The activation energy is *ca.* 30 kcal./mole for the 2 : 4 : 6-trimethylbenzoate and benzoate, for which mechanism $A_{AL}1$ is suggested, and 18 kcal./mole for the formate, in accordance with mechanism $A_{AC}2$. The Arrhenius equation is not followed in the case of the acetate and hydrolysis by the two mechanisms simultaneously is suggested.

The kinetics of acid-catalysed hydrolyses of *tert.*-butyl esters of acids with varying ability to facilitate $A_{AC}2$ hydrolysis, *viz.*, 2 : 4 : 6-trimethylbenzoic, benzoic, acetic, and formic, have been studied.[1] It has been suggested that the activation energy for $A_{AL}1$ hydrolysis is *ca.* 30 kcal./mole and that a transition in mechanism occurs with the acetate, for which, however, the mechanism of hydrolysis is predominantly $A_{AL}1$. This has been established by Bunton and Wood [2] by the use of ^{18}O. Further evidence in support of the suggestion that alkyl–oxygen fission in acid-catalysed hydrolysis is accompanied by an activation energy of *ca.* 30 kcal./mole is available. Bunton, Comyns, Graham, and Quayle [3] find E to be 29·3 kcal./mole for the acid-catalysed hydrolysis of *tert.*-butyl 2 : 4 : 6-triphenylbenzoate, and Dostrovsky and Klein [4] give the value of 30 kcal./mole for the acid-catalysed oxygen exchange of *tert.*-butyl alcohol. In S_N reactions diphenylmethyl shows electron-releasing power comparable with that of *tert.*-butyl, so that its esters should have a similar tendency to $A_{AL}1$ hydrolysis. The formate, however, is known to undergo acyl–oxygen fission.[5] The kinetics of hydrolysis of diphenylmethyl 2 : 4 : 6-trimethylbenzoate, benzoate, acetate, and formate are now reported.

Experimental

Materials.—Diphenylmethanol (15 g.) and 2 : 4 : 6-trimethylbenzoic acid (25 g.) were heated gently during 11 hr. while water escaped. The residue was dissolved in ether, washed with 10% aqueous sodium hydroxide (8 g. of 2 : 4 : 6-trimethylbenzoic acid being recovered), and dried, and the ether evaporated. The crude *diphenylmethyl* 2 : 4 : 6-*trimethylbenzoate* (17 g.) was recrystallised from methanol to constant m. p. (90·5°) (9 g.) (Found : C, 83·7; H, 6·9. $C_{23}H_{22}O_2$ requires C, 83·6; H, 6·7%).

Diphenylmethyl benzoate (crude yield 16 g.), prepared from diphenylmethanol (20 g.), benzoyl chloride (10 ml.), and pyridine (5 ml.), was recrystallised from methanol to constant m. p. (91·5°) (Found : C, 83·4; H, 5·5. Calc. for $C_{20}H_{16}O_2$: C, 83·3; H, 5·6%).

Diphenylmethyl acetate (m. p. 42°) was prepared from diphenylmethanol and acetic anhydride (Found : C, 79·7; H, 6·4. Calc. for $C_{15}H_{14}O_2$: C, 79·6; H, 6·2%).

Diphenylmethyl formate (yield, 96%; b. p. 114°/0·05 mm., n_D^{16} 1·5732; purity, 96%) (Found : C, 79·5; H, 5·8. Calc. for $C_{14}H_{12}O_2$: C, 79·2; H, 5·7%) was prepared from diphenylmethyl chloride (20 g.), sodium formate (15 g.), and formic acid (20 g., 80%).

The purity of the esters was checked by estimation of the acid produced on complete hydrolysis and found to be *ca.* 100% except where stated.

The experimental procedure has been described (Parts I and II). The results are tabulated.

Discussion

The hydrolyses have the kinetic form, rate $\propto [H^+][ester]$. The rates for diphenylmethyl benzoate, acetate, and formate relative to that of the 2 : 4 : 6-trimethylbenzoate are 0·2, 1·6, and 11, respectively, and the values of $\log_{10}(10^6 k_1/c_A)$ (k_1 in sec.$^{-1}$) at 100°

* Part IV, *J.*, 1955, 4020.

[1] Stimson, *Nature*, 1955, **175**, 47; Parts I—IV, *J.*, 1954, 2848; 1955, 2010, 2673, 4020.
[2] Bunton and Wood, *J.*, 1955, 1522.
[3] Bunton, Comyns, Graham, and Quayle, *J.*, 1955, 3817.
[4] Dostrovsky and Klein, *J.*, 1955, 791.
[5] Day and Ingold, *Trans. Faraday Soc.*, 1941, **37**, 686.

are 3·9, 3·2, 4·1, and 4·9 (estimated) in 60% acetone for the 2 : 4 : 6-trimethylbenzoate, benzoate, acetate, and formate, respectively. In view of the resistance to hydrolysis generally found for 2 : 4 : 6-trimethylbenzoic esters of primary alcohols, *i.e.*, by mechanism $A_{Ac}2$, the high rate for the diphenylmethyl ester indicates the incursion of mechanism $A_{Al}1$. If the rate of hydrolysis of diphenylmethyl esters by mechanism $A_{Al}1$ is taken as

First-order rate constants (k_1) for hydrolysis in aqueous acetone.
(C_A and C_E are the concentrations of hydrochloric acid and ester respectively.)

Solvent (% by vol.)	Temp.	10^3C_A (mole/l.)	10^3C_E (mole/l.)	10^3k_1 (min.$^{-1}$)	$10k_1/C_A$ (min.$^{-1}$ l. mole^{-1})	E (kcal./mole)	$\log_{10}A$ (sec.$^{-1}$ mole^{-1} l.)	$\Delta S^{\ddagger}$ (cal./mole/deg.)
Diphenylmethyl 2 : 4 : 6-trimethylbenzoate								
80	109·2°	0·81	1·78	7·1	8·8			
	97·1	1·70	2·10	4·0	2·37	30·4	15·8	11·4
		1·21	2·12	2·86	2·36			
		0·98	2·34	2·45	2·50			
	85·1	1·95	2·12	1·10	0·56	31·2		
		1·30	2·18	0·75	0·57			
Diphenylmethyl benzoate								
80	97·1	1·30	2·72	0·62	0·47			
	85·3	1·16	1·74	0·127	0·110	32·1	15·9	11·8
60	111·3	1·54	1·42	4·8	3·1			
	108·6	1·68	1·40	4·2	2·5			
	97·1	1·54	1·36	1·04	0·67	30·0		
		1·36	1·40	0·99	0·72	31·2	15·1	8·2
	84·5	1·68	1·40	0·29	0·17	30·4		
		1·54	1·42	0·25	0·16			
		1·50	1·42	0·26	0·17			
		1·54	1·36	0·23	0·15			
Diphenylmethyl acetate								
80	109·3	0·88	2·15	1·33	15·1			
	97·1	4·07	1·63	6·3	3·86	31·2	16·3	13·6
	84·8	4·07	1·63	1·68	1·03	28·9		
60	109·2	0·91	2·20	16·6	18·2			
	97·1	2·50	4·03	12·2	4·9	30·0	15·7	11·0
		0·96	1·03	4·55	4·8			
		1·72	2·21	8·7	5·1			
	85·6	1·11	2·25	1·74	1·57	26·5	13·6	1·4
		1·03	2·44	1·63	1·59			
	73·1	1·30	2·24	0·54	0·42	26·0		
	70·7	0·98	2·37	3·30	0·338	25·4	12·9	−1·4
	50·0	2·50	4·03	0·096	0·0384	23·1	11·4	−8·2
40	71·9	2·14	1·77	1·8	0·85			
	50·0	2·25	1·77	0·22	0·098	21·8	11·0	−10·0
Diphenylmethyl formate								
60	97·1	1·04	1·31	36·4	35·1			
		0·52	2·51	18·8	36·1			
	85·0	0·86	1·74	13·0	15·2	18·5	9·8	−16·0
	72·4	1·00	2·24	5·8	5·8	18·7		

E is calculated from the temperature and the mean of the corresponding rates from the line on which it is quoted with the next higher temperature (where it is *ca.* 12° higher) and the corresponding mean rate. For diphenylmethyl benzoate the values 30·0 and 31·2 are obtained from the rate at 97° with those at 111° and 108° respectively. The reliability of E is *ca.* 0·5 kcal./mole.

approximately that of the 2 : 4 : 6-trimethylbenzoate, hydrolysis of these esters by $A_{Al}1$ will be comparable in rate with that of acetates by $A_{Ac}2$, for which the above value [6] is 4·1, and slower than that of formates by $A_{Ac}2$, for which the figure [6] is 5·3 (calc.). By an argument analogous to that used in Part III, this indicates that the mechanism is predominantly $A_{Al}1$ in the case of the benzoate and $A_{Ac}2$ for the formate, in agreement with the results of Day and Ingold.[5] In the case of diphenylmethyl acetate hydrolyses by the two mechanisms are likely to be of comparable rate. This situation is reflected in the activation energy, which for diphenylmethyl 2 : 4 : 6-trimethylbenzoate and benzoate is of

[6] Newling and Hinshelwood, *J.*, 1936, 1359; Timm and Hinshelwood, *J.*, 1938, 869; Davies and Evans, *J.*, 1940, 340.

the order of 30 kcal./mole and for the formate 18·5 kcal./mole, the value [7] usually found for $A_{AC}2$ reactions. The kinetics of hydrolysis of diphenylmethyl acetate do not follow the Arrhenius equation. In 60% acetone, E, calculated from rates at successive temperatures, falls from 30 kcal./mole at 97° to 23 kcal./mole at 50°. This is the behaviour that would be found for two simultaneous reactions of the same kinetic type with considerably different activation energies. The value of E is also different for hydrolyses in solvents of different composition. The values of $\log_{10} A$ and $\Delta S^{\ddagger}$ (cf. Part I) vary in a complementary manner.

It is also noteworthy that, although the diphenylmethyl halides undergo S_N1 reactions faster than the corresponding *tert.*-butyl compounds do, the hydrolyses of diphenylmethyl esters by $A_{AL}1$ are slightly slower (a factor of 0·6 in the case of the 2 : 4 : 6-trimethylbenzoate) than those of *tert.*-butyl esters.[1] Lack of solubility of the 2 : 4 : 6-trimethylbenzoate and benzoate prevents the investigation of their hydrolyses in more aqueous solvents.

The authors thank Mr. S. R. Johns for carrying out some runs on diphenylmethyl benzoate.

THE UNIVERSITY OF NEW ENGLAND,
ARMIDALE, N.S.W., AUSTRALIA. [*Received, April 16th*, 1956.]

[7] Cf. ref. 6; also Smith and Steele, *J. Amer. Chem. Soc.*, 1941, **63**, 3466; Tommila and Hinshelwood, *J.*, 1938, 1806.

---

699. *Radical Exchange in Organometallic Compounds. Part I.* The Replacement of Methyl by Trifluoromethyl.†*

By R. N. HASZELDINE and B. O. WEST.

Trifluoroiodomethane reacts with trimethyl-phosphine, -arsine, or -stibine at room temperature to give the quaternary tetramethyl iodide and dimethyltrifluoromethyl-phosphine, -arsine, or -stibine. By contrast, trimethylamine and trifluoroiodomethane give mainly fluoroform. Possible reaction schemes are considered.

TRISTRIFLUOROMETHYL-PHOSPHINE, -ARSINE, and -STIBINE, prepared by direct reaction of trifluoroiodomethane with phosphorus, arsenic, or antimony, show properties markedly different from their trimethyl analogues. In particular they do not form addition compounds of the usual type and are readily hydrolysed by aqueous base to fluoroform.[1,2] The compounds $CF_3{\cdot}M(CH_3)_2$ and $(CF_3)_2M{\cdot}CH_3$ (M = P, As, or Sb) have now been synthesised in order to study the properties of compounds intermediate between the two extremes $(CF_3)_3M$ and $(CH_3)_3M$.

A convenient route to the compounds $CF_3{\cdot}M(CH_3)_2$ has been found in the reaction of trifluoroiodomethane with trimethyl-phosphine, -arsine, or -stibine. Reaction occurs in the liquid phase at room temperature in absence of a solvent and is accelerated by heat. The products are $CF_3{\cdot}M(CH_3)_2$ (*ca.* 50%), $[(CH_3)_4M]^+I^-$ (*ca.* 50%), and a small amount of fluoroform (1—2% based on trifluoroiodomethane) :

$$2(CH_3)_3M + CF_3I \longrightarrow CF_3{\cdot}M(CH_3)_2 + [(CH_3)_4M]^+I^-$$

The course of the reaction is readily followed because of precipitation of the quaternary iodide. An equilibrium exists at room temperature, and removal of the solid periodically is necessary to cause further deposition of solid and ultimately completion of reaction. There is no indication of replacement of more than one methyl group by trifluoromethyl at room temperature.

* For earlier related work see Haszeldine, "Fluorocarbon Derivatives," R.I.C. Monograph 1956, No. 1.

† For a preliminary publication see *Angew. Chem.*, 1954, **66**, 696.

[1] Bennett, Emeléus, and Haszeldine, *J.*, 1954, 3896 *et seq.*

[2] Emeléus, Haszeldine, and Walaschewski, *J.*, 1953, 1552 *et seq.*; Dale, Moss, Emeléus, and Haszeldine, unpublished results.

The reaction of trifluoroiodomethane with trimethylamine at room temperature is markedly different. Fluoroform is produced in >70% yield, together with tetramethylammonium iodide and an unidentified solid, possibly $[NMe_3I]^+CF_3^-$; dimethyltrifluoromethylamine cannot be detected. This reaction in its early stages gives mainly tetramethylammonium iodide and a larger amount of the unknown solid without the formation of fluoroform, and the volatile products at this stage are only trifluoroiodomethane and trimethylamine.

The most plausible intermediate in these reactions is the quaternary compound of the type $[P(CH_3)_3{\cdot}CF_3]^+I^-$. This was synthesised by the direct combination of dimethyltrifluoromethylphosphine and methyl iodide (see below), and is stable at room temperature, which together with the fact that this iodide is not a product from the reaction of trimethylphosphine and trifluoroiodomethane, requires that the further step or steps in any reaction scheme postulated shall be such that the quaternary iodide is removed completely.

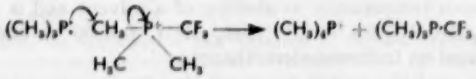
Several qualitative observations are relevant: (*a*) The compound $[P(CH_3)_3{\cdot}CF_3]^+I^-$ is obtained admixed with tetramethylphosphonium iodide when trifluoroiodomethane and trimethylphosphine react in carbon tetrachloride solution. This shows that the quaternary salt can be prepared by a reaction involving a solvent; that it does not react further is due to its insolubility in carbon tetrachloride. (*b*) The compound $[P(CH_3)_3{\cdot}CF_3]^+I^-$ is readily soluble in liquid trifluoroiodomethane at room temperature, and is recovered unchanged on evaporation of the solvent; in particular, neither tetramethylphosphonium iodide nor dimethyltrifluoromethylphosphine is produced. There is thus no direct reaction between the quaternary compound and trifluoroiodomethane. (*c*) Tetramethylphosphonium iodide is also partially soluble in liquid trifluoroiodomethane, but is recovered unchanged on evaporation. (*d*) The compound $[P(CH_3)_3{\cdot}CF_3]^+I^-$ is almost insoluble in trimethylphosphine and not even traces of tetramethylphosphonium iodide are formed even after prolonged contact, but in ethanol some tetramethylphosphonium iodide is formed.

It thus appears that a solvent effect plays an important part in the reaction; since both $[P(CH_3)_4]^+I^-$ and $[P(CH_3)_3{\cdot}CF_3]^+I^-$ are readily soluble in trifluoroiodomethane but only sparingly soluble in trimethylphosphine, trifluoroiodomethane is regarded as the " solvent " for the reaction. The ready solubility of the quaternary compounds explains why the exchange reaction goes to completion in trifluoroiodomethane but not in carbon tetrachloride. The formation of the compound $[P(CH_3)_3{\cdot}CF_3]^+I^-$ could thus be followed by one of two closely related reactions:

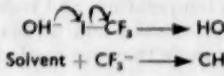
(1) Dissociation of the quaternary compound in trifluoroiodomethane to dimethyltrifluoromethylphosphine and methyl iodide, the latter then reacting with trimethylphosphine to give tetramethylphosphonium iodide:

$$[P(CH_3)_3{\cdot}CF_3]^+I^- \longrightarrow CF_3{\cdot}P(CH_3)_3 + CH_3I \xrightarrow{P(CH_3)_3} [(CH_3)_4P]^+I^-$$

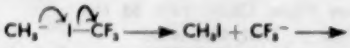
(2) Nucleophilic attack of trimethylphosphine on a methyl group of the quaternary compound:



It was suggested earlier [3] that nucleophilic attack of hydroxide ion on trifluoroiodomethane to give fluoroform involves the relatively positive iodine atom rather than carbon:

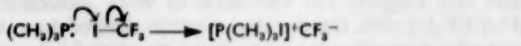


The formation of trifluoromethyl-lithium by reaction of methyl-lithium with trifluoroiodomethane [3] is similarly interpreted:

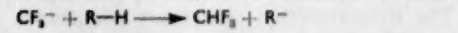


[3] Haszeldine, *J.*, 1952, 4259, and unpublished results.

The formation of the quaternary compound $[P(CH_3)_3{\cdot}CF_3]^+I^-$ can be visualised by a similar nucleophilic attack on iodine :



followed by transformation of the product *via* a transient quinquecovalent state into $[P(CH_3)_3{\cdot}CF_3]^+I^-$. The small amount of fluoroform which is always isolated during the exchange reactions involving trimethyl-phosphine, -arsine, or -stibine, can thus be attributed to a side-reaction in which the trifluoromethyl anion derived from $[P(CH_3)_3I]^+CF_3^-$ attacks a neighbouring molecule RH to abstract hydrogen :



The low yield of fluoroform suggests that the change of $[P(CH_3)_3I]^+CF_3^-$ into $[P(CH_3)_3{\cdot}CF_3]^+I^-$ *via* the quinquecovalent state is rapid. Phosphorus, arsenic, and antimony can accommodate a fifth covalency and this permits the above change.

The situation is different for nitrogen, which cannot form more than four covalent bonds. It is suggested that the initial step in the reaction of trifluoroiodomethane with trimethylamine yields $[N(CH_3)_3I]^+CF_3^-$ by nucleophilic attack on iodine, but that this compound cannot rearrange to $[N(CH_3)_3{\cdot}CF_3]^+I^-$ *via* a quinquecovalent compound. The fluoroalkyl anion is thus able to abstract hydrogen from neighbouring molecules; fluoroform is therefore the major reaction product, and the exchange reaction to give dimethyltrifluoromethylamine does not occur.

Phosphine reacts with trifluoroiodomethane to yield trifluoromethylphosphine so a P–C bond is not essential for reaction; fluoroform is a major product, however, at the elevated temperatures necessary and is probably produced by attack of trifluoromethyl radicals on phosphine.

Dimethyltrifluoromethylphosphine has less co-ordinating power than trimethylphosphine. It does not react with carbon disulphide to form a red compound of the type given by trimethylphosphine and other phosphines,[4] and one trifluoromethyl group thus exerts a marked effect. Dimethyltrifluoromethylphosphine yields a white crystalline compound when shaken with a solution of silver iodide in aqueous potassium iodide at *ca.* 0°, but the solid dissociates so readily that it could not be obtained in a form suitable for analysis. It is probably $[AgI,CF_3{\cdot}P(CH_3)_2]_4$ by analogy with complexes [5] of the general type $[AgI{\leftarrow}PR_3]_4$. The corresponding trimethylphosphine–silver iodide complex is much more stable at room temperature, and the decrease in stability on replacement of a methyl by a trifluoromethyl group is attributed to the inductive effect of the CF_3 group which makes the unshared electron pair of the phosphorus atom less available for co-ordination. Studies on the relative co-ordinating powers of the compounds $P(CH_3)_3$, $CF_3{\cdot}P(CH_3)_2$, $(CF_3)_2P{\cdot}CH_3$, and $P(CF_3)_3$ with platinum chloride would be interesting, since there may be a gradual change in co-ordination from a single σ-bond in the trimethylphosphine complexes to complexes involving double bonds between ligand and metal as has been postulated [6] for the complexes of platinum with strongly electronegative ligands such as phosphorus trifluoride.

Tristrifluoromethylphosphine is hydrolysed instantly by aqueous base at room temperature, whereas hydrolysis of dimethyltrifluoromethylphosphine to fluoroform requires, for completion, prolonged contact with concentrated base at 100°.

Dimethyltrifluoromethylarsine failed to yield a silver iodide complex under any conditions tried. It gave fluoroform only slowly when treated with concentrated aqueous base at room temperature, whereas tristrifluoromethylarsine is hydrolysed quantitatively in a few minutes under comparable conditions. Dimethyltrifluoromethylstibine evolves the theoretical amount of fluoroform with cold aqueous base, though less rapidly than does tristrifluoromethylstibine. The ease of hydrolysis is $CF_3{\cdot}P(CH_3)_2 < CF_3{\cdot}As(CH_3)_2 < CF_3{\cdot}Sb(CH_3)_2$, the converse, as expected, of the ease of complex formation with silver iodide.

[4] Brown and Harris, *J. Amer. Chem. Soc.*, 1949, **71**, 2751; Davies and Walters, *J.*, 1935, 1786.
[5] Mann, Purdie, and Wells, *J.*, 1937, 1828.
[6] Chatt *et al.*, *Nature*, 1950, **165**, 637; *J.*, 1955, 4456.

The difficulty of separation by distillation of compounds of the $CF_3 \cdot M(CH_3)_2$ type from trifluoroiodomethane is much greater than would be expected from the boiling-point differences, and this suggests the formation of weak molecular complexes of the type $[CF_3 \cdot (CH_3)_2M^+ - (ICF_3)^-]$ with the donated electron derived from the lone pair of electrons in M. Such complex formation has been shown to occur [7] between a polyfluoroiodoalkane and a neutral-molecule Lewis base such as an ether or an alcohol, and is of the donor–acceptor type with formation of a weak covalent bond.

Quaternary compounds $[CF_3 \cdot M(CH_3)_3]^+I^-$ have been prepared by reaction of the compounds $CF_3 \cdot M(CH_3)_2$ (M = P or As) with methyl iodide at room temperature in absence of a solvent. The ease of quaternary formation is, qualitatively, $(CH_3)_3P > CF_3 \cdot P(CH_3)_2 > CF_3 \cdot As(CH_3)_2$. The trifluoromethyl quaternary compounds are white crystalline solids which are readily soluble in water and sparingly soluble in ethanol. Both aqueous and ethanolic solutions precipitate silver iodide immediately on treatment with aqueous silver nitrate. The readiness with which the above quaternary compounds are formed can be attributed to the ease of heterolysis of the carbon–iodine bond in methyl iodide. As pointed out earlier, quaternary salt formation involving trifluoroiodomethane probably involves heterolysis of the carbon–iodine bond in a sense opposite to that in methyl iodide, and the quaternary compound reacts further in trifluoroiodomethane solution.

The preparation and properties of the compounds $(CF_3)_2M \cdot CH_3$ will be described in Part II of this series.

Experimental

Reactions were carried out in sealed Pyrex tubes with complete exclusion of moisture and air. Volatile products were manipulated in a vacuum-apparatus. Trifluoroiodomethane was prepared from silver trifluoroacetate. [8]

Fluorine was determined by titration of fluorosilicic acid with thorium nitrate, with sodium alizarinsulphonate as indicator. Arsenic, phosphorus, or antimony did not interfere if their salts present after sodium fusion of the compound and treatment with water were oxidised by hydrogen peroxide; fluorosilicic acid was then separated by steam-distillation.

Reaction of Trifluoroiodomethane with Trimethylphosphine.—In a typical small-scale experiment trimethylphosphine (1·00 g., 13 mmoles) was sealed in a 40-ml. Pyrex tube with trifluoroiodomethane (4·88 g., 25 mmoles). A white crystalline solid was rapidly formed below the surface of the liquid as soon as the temperature approached that of the room, and reaction was substantially complete within 30 min. The volatile products were removed after 17 hr. and fractionated *in vacuo*, to give dimethyltrifluoromethylphosphine (0·85 g., 50%; purified as described below), fluoroform (0·032 g., 2% based on trifluoroiodomethane), and trifluoroiodomethane (3·46 g., 71%). The residual solid was identified as tetramethylphosphonium iodide (1·46 g., 50%) by comparison of its infrared spectrum with that of a sample prepared from trimethylphosphine and methyl iodide; it also gave the mercuric iodide complex [9] $[(CH_3)_4P]I,2HgI_2$ as yellow prisms, m. p. 172° (from ethanol).

Trifluoroiodomethane reacts only slowly with trimethylphosphine in the vapour phase.

Purification and Properties of Dimethyltrifluoromethylphosphine.—Some difficulty was experienced in removing the last traces (2—3%) of trifluoroiodomethane from dimethyltrifluoromethylphosphine by distillation *in vacuo*, and the purity of the last compound is thus best assessed by means of its infrared spectrum. The following procedure was adopted to obtain a sample of analytical purity. Trifluoroiodomethane was allowed to react with an excess of trimethylphosphine (mole ratio 1 : 3), and the dimethyltrifluoromethylphosphine obtained by preliminary fractionation was condensed *in vacuo* on to a large excess of finely powdered silver iodide (10 g. per g. of phosphine). The volatile material which did not react with the silver iodide at room temperature was then removed and condensed on to a fresh portion of silver iodide. Successive treatments with silver iodide in this way separated most of the dimethyltrifluoromethylphosphine from the trifluoroiodomethane. The dimethyltrifluoromethylphosphine was recovered when its silver iodide complex was heated *in vacuo*. Traces of trimethylphosphine were removed from the dimethyltrifluoromethylphosphine by utilising the fact that the dissociation pressure of the dimethyltrifluoromethylphosphine silver iodide

[7] Haszeldine, *J.*, 1953, 2622.
[8] Haszeldine, *J.*, 1951, 584.
[9] Cahours and Hofmann, *Annalen*, 1857, **104**, 31.

complex is considerably greater at 20° (approx. 25 mm.) than that of the corresponding trimethylphosphine complex (approx. 2 mm.); the fluoroalkylphosphine can thus be removed preferentially from silver iodide.

Pure *dimethyltrifluoromethylphosphine* (Found: F, 43·5%; *M*, 130·5. $C_3H_6F_3P$ requires F, 43·8%; *M*, 130·0) is a colourless liquid whose vapour pressure over the range 18—47° is represented by the equation $\log_{10} p$ (mm.) = 7·630 − 1519/*T*, whence the b. p. is 46·8°, the latent heat of vaporisation is 6950 cal./mole, and Trouton's constant is 21·7. The phosphine reacts with air to give a solid, presumably the oxide, but can be heated in absence of air up to 240° for 48 hr. without decomposition or disproportionation. It was decomposed by fusion with sodium for analysis.

Dimethyltrifluoromethylphosphine fails to react with carbon disulphide at room temperature (48 hr.) or at 100° (1 hr.), or when their ethanolic solutions are mixed at room temperature.

There was no visible reaction at room temperature when dimethyltrifluoromethylphosphine (0·18 g.) in anhydrous ether (3 ml.) was shaken in a sealed tube with a 20% solution of silver iodide in aqueous potassium iodide (3 ml.). White needles were formed at the interface of the liquid when the mixture was shaken and cooled to 0—5°, and redissolved on warming.

The solid was separated by filtration at low temperature, but decomposed rapidly during filtration and attempts to purify it failed. The reaction of liquid dimethyltrifluoromethylphosphine with solid silver iodide at room temperature or just below caused the silver iodide to become white in places. Vapour-pressure measurements carried out on a sample of this material prepared in a glass bulb attached to a spoon gauge gave a value of 25 mm. for the vapour pressure of the complex at 20°. It dissociated too rapidly to enable it to be manipulated for analysis.

Reaction of Trifluoroiodomethane with Trimethylarsine.—Into each of three Carius tubes (185 ml. capacity) were condensed trifluoroiodomethane (9·00 g., 46 mmoles) and trimethylarsine (4·33 g., 36 mmoles). The sealed tubes were kept at room temperature (24 hr.). White needles had been formed in the liquid phase after 1 hr., but the rate of formation of the solid was much less than that from the corresponding reaction with trimethylphosphine. The volatile products were combined and transferred to a 200 ml. stainless-steel autoclave and heated at 50—55° (78 hr.). Fractionation then gave trifluoroiodomethane (20·8 g., 106 mmoles), fluoroform (0·061 g., 0·6%), and crude dimethyltrifluoromethylarsine (7·8 g., 41%) contaminated by trifluoroiodomethane (2%). Further distillation through a packed column, followed by repeated distillation *in vacuo*, gave *dimethyltrifluoromethylarsine* (4·9 g., 26%) (Found: F, 32·1%; *M*, 173. $C_3H_6F_3As$ requires F, 32·7%; *M*, 174), shown by infrared spectroscopic examination to be free from trifluoroiodomethane. The vapour pressure of dimethyltrifluoromethylarsine is given by the equation $\log_{10} p$(mm.) = 7·3737 − 1487/*T*, whence the b. p. is calculated as 58·0°, the latent heat of vaporisation is 6800 cal./mole, and Trouton's constant is 20·6. The solid formed during the reaction was shown to be tetramethylarsonium iodide (11·8 g., 42%) by comparison of its infrared spectrum with that of a specimen prepared by the direct reaction of trimethylarsine with methyl iodide.

Dimethyltrifluoromethylarsine failed to react with a solution of silver iodide in aqueous potassium iodide at 20° or at 0°. The trimethylarsine–silver iodide complex has a higher dissociation pressure at 20° (approx. 15 mm.) than the trimethylphosphine complex (approx. 2 mm.), and the arsenic complexes are clearly less stable than their phosphorus analogues.

Reaction of Trifluoroiodomethane with Trimethylstibine.—Trifluoroiodomethane (6·0 g., 31 mmoles) and trimethylstibine (5·0 g., 30 mmoles), sealed in a 300-ml. Pyrex tube, began to deposit needles after 1 hr. The rate of reaction was roughly comparable with that with trimethylarsine. The volatile products were removed after 40 days and fractionated *in vacuo*, to give trifluoroiodomethane (2·8 g.), fluoroform (0·02 g., 1%), and crude dimethyltrifluoromethylstibine (50%). The last fraction was redistilled through a packed column in nitrogen, to give *dimethyltrifluoromethylstibine* (1·36 g., 21%) (Found: F, 26·0%; *M*, 219. $C_3H_6F_3Sb$ requires F, 25·8%; *M*, 221) as a colourless liquid, spectroscopically free from trifluoroiodomethane. The solid (4·6 g., 50%) was identified spectroscopically as tetramethylstibonium iodide.

The vapour pressure of dimethyltrifluoromethylstibine at 16—86° is given by the equation $\log_{10} p$(mm.) = 7·4403 − 1636/*T*, whence the b. p. is calculated as 85·8°, the latent heat of vaporisation is 7490 cal./mole, and Trouton's constant is 20·9.

Reaction of Trifluoroiodomethane with Trimethylamine.—Trifluoroiodomethane (6·62 g., 34 mmoles) and trimethylamine (3·96 g., 67 mmoles), sealed in a 400 ml. Pyrex tube, began to

deposit a white solid as soon as the temperature reached that of the room. Distillation of the volatile products after 33 days gave trimethylamine (0·89 g., 23%), trifluoroiodomethane (0·97 g., 15%), and fluoroform (1·82 g., 77% based on trifluoroiodomethane). Spectroscopic examination of the volatile products failed to reveal dimethyltrifluoromethylamine. Infrared spectroscopic examination of the solid (6·9 g.) revealed the presence of tetramethylammonium iodide and an unidentified material containing carbon–fluorine bonds. Almost 80% of the trimethylamine and all the iodine originally present in the trifluoroiodomethane later converted into fluoroform had thus been converted into solid by the end of the reaction.

In a second experiment with trimethylamine (0·79 g.) and trifluoroiodomethane (1·70 g.) the solid (0·13 g.) which had been formed after 5 hr. contained tetramethylammonium iodide and a considerable amount of material shown by spectroscopic examination to contain C–F bonds. Less than 2% of fluoroform had been produced.

Reaction of Trifluoroiodomethane with Phosphine.—Phosphine was prepared in 97% yield by heating phosphorous acid under 40—50 cm. pressure of nitrogen in a flask connected to a trap cooled to −196°.

Trifluoroiodomethane (1·08 g., 5·5 mmoles) and phosphine (0·186 g., 5·5 mmoles), heated at 240° in a 40 ml. Pyrex tube for 4 hr., gave trifluoromethylphosphine (0·072 g., 13%), trifluoroiodomethane (0·284 g., 27%), fluoroform (0·303 g., 79%), hydrogen iodide (0·008 g.), phosphonium iodide (0·11 g.), and phosphorus tri-iodide.

Hydrolysis of Dimethyltrifluoromethyl-phosphine, -arsine, or -stibine.—The stabilities against hydrolysis were examined by shaking these compounds with 20% aqueous sodium hydroxide (5 ml.) in a 40 ml. Pyrex tube. The volatile products were then fractionated *in vacuo* to separate the unchanged phosphine, arsine, or stibine from the fluoroform produced. Fluoride was not liberated. The results are summarised in the annexed Table.

	Wt. (g.)	Temp.	Time (days)	$CF_3{\cdot}M(CH_3)_2$ unchanged (%)	CHF_3 (%)
$CF_3{\cdot}P(CH_3)_2$	0·292	20°	3	93·5	6·5
	0·254	100	6	9	91
$CF_3{\cdot}As(CH_3)_2$	0·220	20	3	91	9
$CF_3{\cdot}Sb(CH_3)_2$	0·160	20	3	0	100

Trimethyltrifluoromethylphosphonium Iodide.—(i) Methyl iodide (0·683 g., 4·8 mmoles) and dimethyltrifluoromethylphosphine (0·995 g., 7·6 mmoles) in a sealed tube began to deposit white needles after 30 min. After 24 days the volatile products were fractionated, giving methyl iodide (0·333 g., 48%), fluoroform (0·004 g., 0·7%), and dimethyltrifluoromethylphosphine (0·670 g., 67%). The solid was *trimethyltrifluoromethylphosphonium iodide* (0·68 g., 52% based on methyl iodide) (Found: C, 17·6; H, 3·3; I, 46·5. $C_4H_9F_3IP$ requires C, 17·6; H, 3·2; I, 46·7%). The solid does not melt below 300° in a sealed evacuated capillary tube. It is very soluble in water, soluble in ethanol and in trifluoroiodomethane, but insoluble in benzene, carbon tetrachloride, ether, dioxan, or chloroform.

(ii) In a second experiment, trifluoroiodomethane (0·25 g.) and trimethylphosphine (0·09 g.) were dissolved in anhydrous carbon tetrachloride (5 ml.). Reaction began as soon as the tube reached room temperature and a pasty mass was produced within 5 min. The solid produced (0·17 g.) was found spectroscopically to contain trimethyltrifluoromethylphosphonium iodide (32% yield) and tetramethylphosphonium iodide (26% yield).

(iii) Tetramethylphosphonium iodide was not produced and no reaction was detected when trimethyltrifluoromethylphosphonium iodide (0·06 g.) was dissolved in trifluoroiodomethane (2·33 g.) and kept at room temperature (14 days).

(iv) Trimethyltrifluoromethylphosphonium iodide (0·120 g., 0·4 mmole), trimethylphosphine (0·051 g., 0·7 mmole), and anhydrous ethanol (5 ml.), kept in a sealed tube at 20° (30 days), yielded a solid containing tetramethylphosphonium iodide (76% yield) and trimethyltrifluoromethylphosphonium iodide (34% yield).

(v) Trimethyltrifluoromethylphosphonium iodide (0·130 g., 0·6 mmole) did not dissolve appreciably in trimethylphosphine (0·184 g., 2·4 mmoles), or react with it during 3 days at 20°. Spectroscopic examination gave no evidence of tetramethylphosphonium iodide.

Trimethyltrifluoromethylarsonium Iodide.—Dimethyltrifluoromethylarsine (0·45 g., 2·6 mmoles) and methyl iodide (0·36 g., 2·5 mmoles) deposited a small amount of a white crystalline solid after 30 min. After 12 hr. at room temperature the amount of solid had only slightly increased. The tube was therefore heated at 85° (14 hr.) and the amount of solid appreciably increased. Infrared spectroscopy of the *trimethyltrifluoromethylarsonium iodide* (0·03 g., 4%) (Found: C,

15·5; H, 2·6. $C_4H_9F_3IAs$ requires C, 15·1; H, 2·9%) showed it to be free from tetramethylarsonium iodide. The solid is soluble in water and in ethanol but insoluble in ether and benzene.

One of us (B. O. W.) is grateful to the Master and Fellows of Gonville and Caius College, Cambridge, for the award of a Rhondda Research Studentship, and the University of Adelaide for leave of absence.

UNIVERSITY CHEMICAL LABORATORY, CAMBRIDGE. [*Received, April 24th*, 1956.]

---

700. *Fluorine-substituted Polycyclic Compounds.*

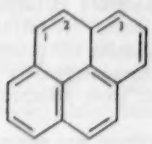
By G. M. BADGER and J. F. STEPHENS.

Attempts to fluorinate three polycyclic hydrocarbons with *p*-tolyliododifluoride according to the method of Garvey, Halley, and Allen [1] have been unsuccessful. Very small yields have been obtained by using modified conditions; and when chlorinated solvents were used some chlorination of the hydrocarbons resulted.

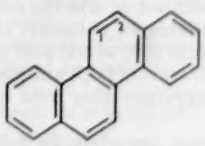
A number of fluorine-substituted polycyclic compounds has been prepared by the Schiemann reaction.

FLOURINE-SUBSTITUTED polycyclic aromatic compounds are of possible interest in experimental carcinogenesis, and it was therefore desirable to attempt the preparation of a series of such compounds by the direct substitution of the hydrocarbons, using *p*-tolyliododifluoride. This reagent was introduced by Bockemuller,[2] who found that with diethylaniline it gives *NN*-diethyl-*p*-fluoroaniline and tetra-*N*-ethylbenzidine. Garvey, Halley, and Allen [1] obtained similar results with a few aromatic hydrocarbons and ketones. For example, in chloroform, pyrene (I) was reported to give a fluoropyrene of unknown orientation, and dipyrenyl. This reaction with pyrene has now been repeated under the conditions given, but only unchanged pyrene could be recovered (Lund and Berg [3] also attempted this reaction, but without success).

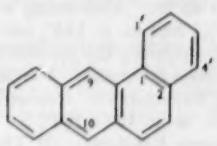
It is possible that some unknown factor may be of critical significance, and a series of experiments was therefore carried out. Reaction did occur when a mixture of aqueous



(I)



(II)



(III)

hydrofluoric acid and chloroform was used as a solvent, but in this case 3-chloropyrene was obtained together with a hydrocarbon, probably 3 : 3′-dipyrenyl. Similarly chrysene (II) was not fluorinated under the reaction conditions specified for other compounds by Garvey, Halley, and Allen; [1] but when a mixture of aqueous hydrofluoric acid and chloroform (or *s*-tetrachloroethane) was used, 2-chlorochrysene was obtained in high yield. Presumably the chlorinated solvent is first attacked by the reagent, liberating chlorine radicals, which then react with the hydrocarbon. The reaction with pyrene was certainly inhibited by the addition of quinol; and the formation of 3 : 3′-dipyrenyl is consistent with the view that a radical mechanism is involved.

A chlorine-free solvent was therefore indicated; when acetic acid was used, pyrene gave 3 : 3′-dipyrenyl together with a little of the desired 3-fluoropyrene. Similarly, 1 : 2-benzanthracene (III) gave a difluoro-1 : 2-benzanthracene, but in very small yield.

[1] Garvey, Halley, and Allen, *J. Amer. Chem. Soc.*, 1937, **59**, 1827.
[2] Bockemuller, *Ber.*, 1931, **64**, 522.
[3] Lund and Berg, *Kgl. Danske Videnskab. Selsk.*, 1946, **22**, No. 15.

In our hands, therefore, the use of *p*-tolyliodofluoride proved unsatisfactory for the preparation of fluorine-substituted polycyclic compounds in reasonable quantity, and the Schiemann [4] reaction was investigated as an alternative route. This reaction involves the conversion of an amine into the diazonium fluoroborate, which is then decomposed by pyrolysis. As a wide variety of amino-substituted compounds is available, this reaction seemed to offer reasonable scope. 3-Fluoropyrene was accordingly prepared from 3-aminopyrene by a method somewhat similar to that used by Lund and Berg,[3] and 2-fluorochrysene from 2-aminochrysene in the same manner. 4'-Amino-1 : 2-benzanthraquinone gave a black diazonium fluoroborate which, on pyrolysis, gave a tar from which only 1 : 2-benzanthraquinone could be isolated. Similarly, 9-aminoanthracene gave only anthraquinone; and 10-amino-1 : 2-benzanthracene gave a tar from which no pure product could be extracted. On the other hand, 4'-amino-1 : 2-benzanthracene was successfully converted into 4'-fluoro-1 : 2-benzanthracene in very small yield.

Experimental

3-Aminopyrene.—A filtered solution, obtained by heating hydrated sodium sulphide (175 g.), anhydrous sodium hydrogen carbonate (58 g.), and ethanol (360 c.c.), was added slowly, with stirring, to 3-nitropyrene (65 g.; Vollmann *et al.*[5]) in boiling ethanol (200 c.c.). After 2 hours' boiling the mixture was concentrated to 250 c.c. and cooled. The product was collected, washed with ethanol and then water, and recrystallised from hexane, to give 3-aminopyrene (46 g.), m. p. 115—117° (Vollmann *et al.*[5] give 117—118°).

2-Aminochrysene.—2-Nitrochrysene (53 g.) was reduced with sodium hydrogen sulphide as described above. After recrystallisation from benzene and from acetone the 2-aminochrysene had m. p. 208—209°. This method was more satisfactory than that of Newman *et al.*,[6] who give m. p. 210—211° (corr.).

10-Amino-1 : 2-benzanthracene.—This was produced by the reduction of 10-nitro-1 : 2-benzanthracene with stannous chloride according to Fieser and Creech.[7] The following procedure for the preparation of the nitro-compound is superior to that described in the literature.[8, 9]

Fuming nitric acid (11 c.c.; *d* 1·5) was added cautiously to redistilled acetic anhydride (32 c.c.) at −70°. The resulting solution was then added, together with urea nitrate (25 mg.), to a suspension of 1 : 2-benzanthracene (32 g.) in redistilled acetic anhydride (40 c.c.), also at −70°. The mixture was stirred while the temperature was allowed to come to 0°, then kept thereat for 48 hr. After being washed with acetic acid the crude 10-nitro-1 : 2-benzanthracene (21 g., 56%) had m. p. 145°, and was suitable for reduction to the amine. A further 4 g. was obtained by pouring the mother-liquors into 50% acetic acid and digesting the precipitate with dilute aqueous ammonia. Further purification of both samples by chromatography on alumina in carbon tetrachloride, followed by recrystallisation from ethanol, gave 10-nitro-1 : 2-benzanthracene, m. p. 163—164°.

Schiemann Reactions.—(i) The following procedure for 3-fluoropyrene was superior to that of Lund and Berg.[3] A solution of 3-aminopyrene (25 g.) in the minimum amount of boiling acetic acid was poured into vigorously stirred 10% hydrochloric acid (500 c.c.). The product was collected, washed with a little 10% hydrochloric acid, and suspended in water (1 l.) and 33% hydrochloric acid (30 c.c.) at 5°. Sodium nitrite (10 g.) in water (120 c.c.) was then added dropwise, during 30 min., to the vigorously stirred suspension at 4—6° (addition of ice). After a further 30 min., sodium fluoroborate (28 g.) in water (200 c.c.) was added slowly with stirring, at 5°. The mixture was warmed on the steam-bath for a few minutes until the precipitate began to coagulate, after which it was rapidly cooled and then allowed to settle at 0° for 12 hr. The resulting product was washed with ice-cold alcohol (20 c.c.) and with ice-cold ether (4 × 20 c.c.) and dried at 35—40°. This dried material was added in 3—4 g. lots, to boiling xylene (500 c.c.), the vigorous reaction being allowed to subside between each addition. The xylene was then removed and the resulting tar extracted with ether. The ethereal solution was

[4] Balz and Schiemann, *Ber.*, 1927, **60**, 1186; see also Roe, *Organic Reactions*, 1949, **5**, 193.
[5] Vollmann, Becker, Corell, and Streeck, *Annalen*, 1937, **531**, 1.
[6] Newman and Cathcart, *J. Org. Chem.*, 1940, **5**, 619.
[7] Fieser and Creech, *J. Amer. Chem. Soc.*, 1939, **61**, 3502.
[8] Barnett and Matthews, *Chem. News*, 1925, **130**, 339.
[9] Fieser and Hershberg, *J. Amer. Chem. Soc.*, 1938, **60**, 1893.

evaporated, and the residue recrystallised once from acetic acid before being chromatographed on alumina in hexane solution. After recrystallisation from hexane and finally from acetic acid, the 3-fluoropyrene was obtained as colourless needles, m. p. 137° (Found: C, 87·5; H, 4·3. Calc. for $C_{16}H_9F$: C, 87·3; H, 4·1%). The *trinitrobenzene complex*, recrystallised from hexane, had m. p. 206° (Found: C, 61·5; H, 2·8; N, 9·9. $C_{16}H_9F,C_6H_3O_6N_3$ requires C, 61·1; H, 2·6; N, 9·7%). A picrate, m. p. 186—187°, was formed in alcohol, but was unstable.

(ii) A boiling solution of 2-aminochrysene (20 g.) in acetone (500 c.c.) was poured into 1·5% hydrochloric acid (2 l.) with vigorous mechanical stirring. The resulting finely divided hydrochloride was then diazotised and converted into the fluoroborate as described above. The resulting diazonium fluoroborate (28 g.) was finely crushed and decomposed in a 500 c.c. flask by direct heating until decomposition started. When the vigorous reaction had abated the temperature was kept at 195° for 1 min. The residue was extracted with benzene, the benzene evaporated, and the product chromatographed on alumina in carbon tetrachloride. The resulting *2-fluorochrysene* (17 g.) had m. p. 192—195°, and after repeated recrystallisation from benzene and from carbon tetrachloride was obtained as colourless prisms, m. p. 197—198° (Found: C, 87·9; H, 4·5; F, 7·9. $C_{18}H_{11}F$ requires C, 87·8; H, 4·5; F, 7·7%).

(iii) 4′-Amino-1 : 2-benzanthracene (4·4 g.) was dissolved in acetone, and 30% hydrochloric acid (5 c.c.) added. The fine yellow precipitate was suspended in water (50 c.c.) and 30% hydrochloric acid (5 c.c.), and diazotised and converted into the fluoroborate as described above. The dry diazonium fluoroborate was suspended in xylene (75 c.c.) which was then boiled for 5 min. The product was chromatographed on alumina in carbon tetrachloride (yield 0·75 g.) and further purified by recrystallisation from ethanol and hexane. *4′-Fluoro-1 : 2-benzanthracene* formed colourless plates, m. p. 170—170·5° (Found: C, 88·3; H, 4·5. $C_{18}H_{11}F$ requires C, 87·8; H, 4·5%).

Direct Substitution of Pyrene.—Only unchanged pyrene was isolated following the attempted fluorination of pyrene with *p*-tolyliododifluoride according to Garvey, Halley, and Allen.[9] The following experiment is typical of several under somewhat different conditions.

A suspension of *p*-iodosotoluene (15 g.) in water (100 c.c.) and hydrofluoric acid (20 c.c.; 46%) was added to a solution of pyrene (10 g.) in chloroform (150 c.c.) at 50° in a Pyrex flask. The flask was then shaken until all the solid had dissolved, an additional 5 c.c. of hydrofluoric acid being added if necessary. After being kept in the dark at room temperature with occasional shaking for 72 hr., the mixture was steam-distilled. The resulting solid was dried and purified by chromatography on alumina in carbon tetrachloride. Evaporation of the eluate gave a yellow solid (5 g.) which was extracted with boiling ethanol. The insoluble fraction was recrystallised from benzene, to give light yellow 3 : 3′-dipyrenyl (?), m. p. 325—326° after softening at 317° (vac.) (Found: C, 95·0; H, 4·8. Calc. for $C_{32}H_{22}$: C, 95·5; H, 4·5%). Vollmann *et al.*[5] give m. p. 319—320°.

The alcohol-soluble fraction was recrystallised successively from acetone, ethanol, and hexane. 3-Chloropyrene (0·5 g.) was obtained as colourless blades, m. p. 119·5—120·5°, not depressed by admixture with a specimen prepared from pyrene and sulphuryl chloride (Vollmann *et al.*[5]). The ultraviolet absorption spectrum in ethanol was identical with that given by Friedel and Orchin.[11]

In a further experiment, a mixture of *p*-iodosotoluene (12·5 g.) in acetic acid (50 c.c.) and 40% hydrofluoric acid (10 c.c.) was added with stirring to pyrene (5 g.) in acetic acid (150 c.c.) at 55°. After 72 hr. the mixture was poured into boiling water, and the product collected. 3 : 3′-Dipyrenyl, m. p. 320—324°, was again isolated, and fractional recrystallisation of the complex with picric acid gave pyrene picrate, m. p. and mixed m. p. 217—219°, and 3-fluoropyrene picrate (30 mg.), m. p. 186—187°, also undepressed by admixture with a specimen prepared as described above.

Direct Substitution of Chrysene.—The following was typical of a number of experiments in which modified conditions were used. A suspension of *p*-iodosotoluene (40 g.) in water (50 c.c.) and 40% hydrofluoric acid (40 c.c.) was added to chrysene (10 g.) in *s*-tetrachloroethane (300 c.c.) at 55°. The reaction was then allowed to proceed at room temperature, in the dark, for 72 hr., after which the mixture was steam-distilled. Purification of the solid by chromatography on alumina, in carbon tetrachloride (yield 7 g.; m. p. 145—153°), followed by recrystallisation from benzene, gave 2-chlorochrysene, m. p. 155—156°, unchanged by further recrystallisation, vacuum-sublimation, or purification through the trinitrobenzene complex, m. p. 164·5—165·5°. It was identified by a direct comparison with a specimen prepared from chrysene and sulphuryl

[10] Stanley, McMahon, and Adams, *J. Amer. Chem. Soc.*, 1933, **55**, 706.
[11] Friedel and Orchin, "Ultraviolet Spectra of Aromatic Compounds," Wiley, New York, 1951.

chloride.[12] The trinitrobenzene complex prepared from authentic 2-chlorochrysene had m. p. 167—168°, but it dissociated too readily to be analysed. Similarly the picrate had m. p. 142—143°, and was also unstable.

Direct Substitution of 1 : 2-*Benzanthracene.*—No success was obtained by the general method of Garvey, Halley, and Allen.[1]

A solution of *p*-iodosotoluene (12·5 g.) in acetic acid (50 c.c.) and 40% hydrofluoric acid (10 c.c.) was added with stirring to 1 : 2-benzanthracene (5 g.) in glacial acetic acid (200 c.c.). After 72 hr. the mixture was poured into water, and the solid collected, steam-distilled to remove *p*-iodotoluene, and extracted with carbon tetrachloride. Evaporation of the solvent, followed by recrystallisation from acetic acid and sublimation at 100°/0·03 mm., gave a *difluoro*-1 : 2-*benzanthracene* (25 mg.), m. p. 144—144·5° (Found: C, 81·8; H, 3·9. $C_{18}H_{10}F_2$ requires C, 81·8; H, 3·8%).

Microanalyses were carried out by the C.S.I.R.O. Microanalytical Laboratory, Melbourne. We are also indebted to the University of Adelaide Anti-Cancer Committee for a maintenance grant (to J. F. S.).

UNIVERSITY OF ADELAIDE, SOUTH AUSTRALIA. [*Received, May 7th,* 1956.]

[12] Vollmann and Becker, Fr. Pat. 793,893; *Chem. Abs.*, 1936, **30**, 4516.

---

701. *The Formation of* iso*But-1-enyl Radicals from* iso*But-1-enylsilver. Part II.**

By F. GLOCKLING.

*iso*But-1-enyl radicals formed by the heterogeneous decomposition of *iso*but-1-enylsilver are shown by isotope studies with $C_2H_5{\cdot}OD$ and $C_2D_5{\cdot}OH$ to attack the O–H (or O–D) bond of ethanol rather than the α-C–H (or C–D) bond. In contrast methyl radicals attack the α-C–H bond in agreement with previous observations.[1] Styrene is polymerised by decomposing *iso*but-1-enylsilver, while α-methylstyrene is unaffected. Qualitative experiments on the co-ordination properties of *iso*but-1-enylsilver are described.

IN Part I * it was shown that *iso*but-1-enylsilver is produced from *iso*but-1-enyltriethyllead and silver nitrate in ethanol: $Et_3Pb{\cdot}CH{:}CMe_2 + AgNO_3 \longrightarrow Me_2C{:}CHAg + Et_3Pb{\cdot}NO_3$. Evidence was produced that *iso*but-1-enylsilver decomposes above −20°, forming silver and *iso*but-1-enyl radicals, $Me_2C{:}CH{\cdot}$, of which some 10% dimerise to $(Me_2C{:}CH)_2$. The main reaction product is *iso*butene and in order to account for the high yield of *iso*butene relative to *iso*but-1-enylsilver (the lead alkyl being present in excess) the following radical-chain reaction was postulated:

$$Me_2C{:}CH{\cdot} + EtOH \longrightarrow Me_2C{:}CH_2 + EtO{\cdot} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$Et_3PbCH{:}CMe_2 + EtO{\cdot} \longrightarrow Et_3PbOEt + Me_2C{:}CH{\cdot} \quad . \quad . \quad . \quad (2)$$

The main object of the present work has been to clarify reaction (1), which involves abstraction of the hydroxylic-hydrogen atom from ethanol, forming *iso*butene and an ethoxy-radical. It was shown in Part I that in the presence of ethyl deuteroxide, EtOD, the gaseous product was 1-deutero*iso*butene, indicating that the O–D rather than an α-C–H bond is attacked by the *iso*but-1-enyl radical. The same result has now been obtained with methyl deuteroxide as solvent. However, the reaction is heterogeneous, *iso*but-1-enylsilver being largely insoluble in the concentration range studied, and silver being formed as the reaction proceeds. It was therefore considered possible that isolation of 1-deutero*iso*butene had resulted from a hydrogen–deuterium exchange and that in fact the radical-transfer reaction involved the formation of hydroxyethyl radicals: $Me_2C{:}CH{\cdot} + EtOH \longrightarrow Me_2C{:}CH_2 + CH_3{\cdot}CH(OH){\cdot}$.

* Part I, *J.*, 1955, 716.

[1] Kharasch, Rowe, and Urry, *J. Org. Chem.*, 1951, **16**, 905.

In order to resolve this problem it was first established that *iso*butene does not undergo hydrogen–deuterium exchange in the presence of ethyl deuteroxide and the solid reaction products (Ag, $Et_3Pb{\cdot}NO_3$, etc.) in one week at room temperature. More convincing proof that reaction (1) does involve the hydroxylic-hydrogen atom of ethanol was then obtained by using pentadeuteroethanol as solvent. This showed strong C–D and O–H absorption bands in the infrared spectrum, the C–H stretching frequency being only just detectable. *iso*Butene obtained from this reaction showed *no* C–D absorption in the infrared spectrum. This observation, combined with the fact that ethyl deuteroxide affords 1-deutero*iso*-butene, can only be regarded as proof that reaction (1) does occur.

This result is unexpected, particularly in view of the closely related work of Kharasch and his co-workers [1] who studied the reactions of methyl radicals (from diacetyl peroxide) with propan-2-ol containing some 40 mole % of $Me_2CH{\cdot}OD$, and *tert.*-butyl alcohol containing 4 mole % of $Me_3C{\cdot}OD$. In each case the methane formed gave no deuterium oxide on combustion. These authors also refer to the reaction of methyl radicals in propan-2-ol enriched with 2-deuteropropan-2-ol and report that a mixture of methane and deuteromethane is formed. The earlier work of Gellison and Hermans [2] on the decomposition of benzoyl peroxide in *iso*butan-1-ol apparently led to products such as $Me_2CH{\cdot}CH_2{\cdot}O{\cdot}C_6H_4{\cdot}CO_2H$, indicating that the hydroxylic-hydrogen atom was attacked by radicals derived from the peroxide.

Kharasch's work is perhaps open to the criticism that only partly deuterated alcohols were used. However, in the present work it was found that in virtually 100% ethyl deuteroxide methyl radicals give methane free from deuterium, while reaction of methyl radicals with pentadeuteroethanol gave monodeuteromethane, thus confirming Kharasch's results for the behaviour of methyl radicals in isotopically mixed alcohols. It thus appears that it is *iso*but-1-enyl radicals which behave anomalously by attacking O–H or O–D rather than C–H or C–D bonds.

In view of this anomaly a demonstration that *iso*but-1-enylsilver decomposes with the formation of radicals rather than ions (which would naturally attack O–H bonds) was important. When the reaction is carried out in the presence of styrene, the yield of *iso*-butene is approximately halved and polystyrene is produced. Infrared examination of a film of the polystyrene did not provide convincing evidence about the end-groups present, though there was a strong absorption at 4·3 μ, not normally found in polystyrene. α-Methylstyrene, which is not polymerised by free-radical initiators, did not affect the yield of *iso*butene, nor was any polymer isolated.

Attempts have been made to stabilise *iso*but-1-enylsilver by co-ordination. Thus, if a large excess of trimethylamine is added to the orange sparingly soluble *iso*but-1-enylsilver at −78° a clear colourless solution is formed which, at room temperature, slowly deposits metallic silver. Co-ordination is apparently quite weak since at −30° trimethylamine was readily lost *in vacuo* with reprecipitation of the alkenylsilver. 2 : 2′-Dipyridyl behaved similarly, though deposition of silver occurred much more slowly at room temperature. Triethylphosphine also gave a colourless solution at −78° from which silver separated at −40°.

Experimental

Pentadeuteroethanol, etc.—Dideuteroacetylene was converted into tetradeuteroethylene *via* 1 : 2-dibromotetradeuteroethane, essentially by the methods described by Leitch and Morse [3] except that purifications were effected by fractional condensation so that the deuterated intermediates were never removed from the vacuum-apparatus.

Pentadeuteroethyl bromide was obtained in essentially quantitative yield when tetradeuteroethylene (4·5 l. at N.T.P.) and deuterium bromide (4·5 l.) were mixed and irradiated overnight with a 150 w incandescent lamp. It was purified by condensation in a trap cooled to −95°.

This fully deuterated ethyl bromide (22 g.) was converted into the acetate pentadeuteroethyl acetate when shaken with silver acetate (38 g.) and acetic acid (45 c.c.) in a sealed bulb, equipped with a break-seal, for 3 days at 100°. Most of the acetic acid was separated from the deuterated ester by repeated evaporation from a bath at −40°. The crude acetate was

[2] Gellison and Hermans, *Ber.*, 1925, **58**, 765.
[3] Leitch and Morse, *Canad. J. Chem.*, 1952, **30**, 924.

hydrolysed by shaking it in a sealed bulb at 100° for 6 hr. with sodium hydroxide (12 g.) and water (13 c.c.). Volatile materials were separated by pumping and dried, first, over anhydrous magnesium sulphate, then in a large bulb containing calcium turnings. The pentadeuteroethanol thus obtained was kept over fresh calcium until no increase in hydrogen pressure was observed during 4 hr. (yield, 7 g.) (traces of mercury appear to accelerate greatly the rate of reaction of the alcohol with calcium).

An infrared spectrum on this deuterated ethanol showed a weak C–H stretching frequency at 3·44 μ and very strong absorption bands at 3·04 and 4·5 μ corresponding to the O–H and C–D stretching frequencies respectively. Strong absorption also occurred at 4·78 μ, similar to that observed in 2-deuteropropan-2-ol.[4]

Decomposition of iso*But-1-enylsilver in Pentadeuteroethanol.*—Dry, finely powdered silver nitrate (0·02 g.) was dissolved in the deuterated alcohol (3 g.), and *iso*but-1-enyltriethyl-lead (0·35 g.) distilled on to the mixture. The orange *iso*but-1-enylsilver was allowed to decompose overnight, the volatile materials being separated. The condensable gas which passed through a trap cooled to −95° was collected (13·5-N-c.c.) and shown to have an infrared spectrum identical with that of *iso*butene.

Reactions of Methyl Radicals with Ethyldeuteroxide and Pentadeuteroethanol.—Diacetyl peroxide[5] (0·05 g.), which had been crystallised three times from carbon tetrachloride–pentane and freed from solvents by pumping at −10° for several hours, was treated with the alcohol, and the mixture heated at 60—70° for 8 hr. The non-condensable gas was separated and examined spectroscopically. From ethyl deuteroxide, methane was produced; the non-condensable gas from pentadeuteroethanol showed a strong C–D stretching frequency.

Department of Chemistry, The University, Durham. [*Received, May 8th*, 1956.]

[4] Amer. Pet. Inst. Spectrogram No. 1146.
[5] Edwards and Mayo, *J. Amer. Chem. Soc.*, 1950, **72**, 1265.

---

702. *Polypeptides. Part IV.* The Self-condensation of the Esters of Some Peptides of Glycine and Proline.*

By H. N. Rydon and P. W. G. Smith.

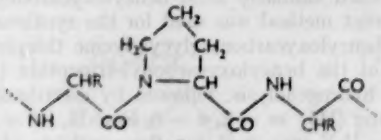
The ethyl esters of the two dipeptides, the three tripeptides, and two tetrapeptides containing glycine and one proline residue have been synthesised. On self-condensation the dipeptide esters give the anhydride (IV) as the major product, this being formed much more readily from the ester of glycylproline than from that of prolylglycine; this difference is ascribed to the more favourable conformation of the side-chain and the greater degree of fixation of the atoms in the former peptide ester. The self-condensation of the tripeptide esters gives complex mixtures in which both the anhydride (IV) and piperazine-2 : 5-dione are present. L-Prolyldiglycylglycine ethyl ester is resistant to self-condensation.

The introduction into a peptide chain of a residue of proline, or hydroxyproline, has a profound effect on its geometry owing to the fixation of the two atoms of the pyrrolidine ring and the two atoms adjacent to it in the peptide chain; thus, for example, a proline-containing polypeptide (I) cannot adopt the fully extended conformation (II) available to a proline-free peptide. The effect of introducing such residues into a peptide chain has been discussed in general terms by Edsall,[1] who points out that they not only influence the geometry of the molecule, interfering with the attainment of helical (and likewise, necessarily, other) conformations and serving even to bend the chain back on itself, but also with the potentialities of the molecule for hydrogen-bonding; these considerations are of particular importance for the conformation of the molecules of the proline-rich fibrous proteins of the

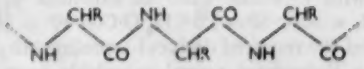
* Part III, Heaton, Rydon, and Schofield, *J.*, 1956, 3157.

[1] Edsall, *J. Polymer Sci.*, 1954, **12**, 253.

collagen–gelatin group.[2] In dipeptides the presence of proline residues results [3,4] in remarkably ready cyclisation to anhydrides (piperazine-2 : 5-diones) under conditions which leave other dipeptides quite unaffected. It may also be of significance that such naturally occurring cyclic oligopeptides as gramicidin-S and the tyrocidines [5] and phalloidine [6] contain residues of proline or hydroxyproline.



(I)

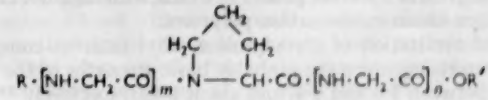


(II)

In this paper we describe the extension of our earlier study [7] of the self-condensation of the esters of glycine peptides to the esters of a representative series of peptides containing also proline, *viz.*, glycylproline, prolylglycine, diglycylproline, glycylprolylglycine, prolylglycylglycine and prolyldiglycylglycine.

Bergmann and his colleagues prepared glycyl-L-proline [8] and glycyl-DL-proline [9] by coupling benzyloxycarbonylglycyl chloride with proline; in our hands this procedure was unsatisfactory, as also was its obvious modification employing proline ethyl ester. Neither the thiothiazolidone method of Cook and Levy,[10] which was so successful in the preparation of polyglycine esters,[7] nor the mixed anhydride procedure of Boissonnas [11,12] was satisfactory when applied to proline or its ethyl ester. Finally, the method of Wieland, Schäfer, and Bokelmann [13] was adopted and proved very satisfactory; coupling of *N*-benzyloxycarbonylglycine thiophenyl ester with L- and DL-proline afforded the benzyloxycarbonyl-peptides (III; $m = 1$, $n = 0$, R = Ph·CH_2·O·CO, R′ = H) in good yield; hydrogenolysis, followed by esterification,[14] then afforded the required L- and DL-glycylproline ethyl esters (III; $m = 1$, $n = 0$, R = H, R′ = Et), isolated as their hydrochlorides.

By contrast, the Boissonnas procedure [11,12] proved entirely satisfactory in the isomeric series, condensation of the mixed anhydrides from ethyl chloroformate and L- and DL-benzyloxycarbonylproline with glycine ethyl ester yielding benzyloxycarbonyl-dipeptide esters (III; $m = 0$, $n = 1$, R = Ph·CH_2·O·CO, R′ = Et) in excellent yield. Direct hydrogenation of these derivatives gave rather impure products and it was found best to hydrolyse them first to the corresponding acids which were then hydrogenolysed to the free peptides



(III)

(III; $m = 0$, $n = 1$, R = R′ = H), these finally being re-esterified to the required L- and DL-prolylglycine ethyl esters (III; $m = 0$, $n = 1$, R = H, R′ = Et), isolated as their hydrochlorides.

[2] See, *e.g.*, Astbury, *J. Int. Soc. Leather Chem.*, 1940, **24**, 69; Pauling and Corey, *Proc. Nat. Acad. Sci. U.S.A.*, 1951, **37**, 272; Ramachandran and Kartha, *Nature*, 1954, **174**, 269; 1955, **176**, 593; Ramachandran, *ibid.*, 1956, **177**, 710; Rich and Crick, *ibid.*, 1955, **176**, 915; Cowan, McGavin, and North, *ibid.*, p. 1062.
[3] Abderhalden and Nienburg, *Fermentforsch.*, 1933, **13**, 573.
[4] E. L. Smith and Bergmann, *J. Biol. Chem.*, 1944, **153**, 627.
[5] Reviewed by Synge, *Quart. Rev.*, 1949, **3**, 259.
[6] Lynen and Wieland, *Annalen*, 1938, **533**, 93; Wieland and Witkop, *ibid.*, 1940, **543**, 171.
[7] Rydon and P. W. G. Smith, *J.*, 1955, 2542.
[8] Bergmann, Zervas, Schleich, and Leinert, *Z. physiol. Chem.*, 1934, **212**, 72.
[9] Bergmann and Fruton, *J. Biol. Chem.*, 1937, **117**, 189.
[10] Cook and Levy, *J.*, 1950, 646.
[11] Boissonnas, *Helv. Chim. Acta*, 1951, **34**, 874.
[12] Vaughan, *J. Amer. Chem. Soc.*, 1951, **73**, 3547.
[13] Wieland, Schäfer, and Bokelmann, *Annalen*, 1951, **573**, 99.
[14] Synge, *Biochem. J.*, 1948, **42**, 99.

In the tripeptide series, coupling of the mixed anhydride from benzyloxycarbonylglycine and ethyl chloroformate with L- and DL-prolylglycine ethyl esters yielded the benzyloxycarbonyl esters (III; $m = n = 1$, R = $Ph{\cdot}CH_2{\cdot}O{\cdot}CO$, R′ = Et) which were then hydrogenolysed to the required L- and DL-glycylprolylglycine ethyl esters (III; $m = n = 1$, R = H, R′ = Et), isolated as their hydrochlorides. L-Prolylglycylglycine ethyl ester (III; $m = 0$, $n = 2$, R = H, R′ = Et) was synthesised similarly from benzyloxycarbonyl-L-proline and glycylglycine ethyl ester. A different method was used for the synthesis of diglycylproline ethyl ester. Condensation of benzyloxycarbonylglycylglycine thiophenyl ester with L-proline gave an excellent yield of the benzyloxycarbonyl-tripeptide (III; $m = 2$, $n = 0$, R = $Ph{\cdot}CH_2{\cdot}O{\cdot}CO$, R′ = H); hydrogenolysis, followed by esterification, afforded the required diglycyl-L-proline ethyl ester (III; $m = 2$, $n = 0$, R = H, R′ = Et).

The Boissonnas mixed-anhydride procedure [11,12] was used for the synthesis of the tetrapeptide esters. Coupling of the mixed anhydride from benzyloxycarbonylglycylglycine and ethyl chloroformate with L- and DL-glycylproline ethyl esters afforded the benzyloxycarbonyl-tetrapeptide esters (III; $m = 3$, $n = 0$, R = $Ph{\cdot}CH_2{\cdot}O{\cdot}CO$, R′ = Et), hydrogenolysis of which gave the required L- and DL-triglycylproline ethyl esters (III; $m = 3$, $n = 0$, R = H, R′ = Et), isolated as their hydrobromides. L-Prolyldiglycylglycine ethyl ester (III; $m = 0$, $n = 3$, R = H, R′ = Et) was prepared similarly from benzyloxycarbonyl-L-proline and diglycylglycine ethyl ester. In view of the poor yield obtained in the Boissonnas synthesis of triglycyl-L-proline ethyl ester the thiophenyl ester route [13] to this compound was also explored; triglycyl-L-proline (III; $m = 3$, $n = 0$, R = R′ = H) was obtained in very satisfactory yield by condensing benzyloxycarbonylglycylglycine thiophenyl ester with glycyl-L-proline and hydrogenolysing the product, but unexpectedly proved very resistant to esterification.

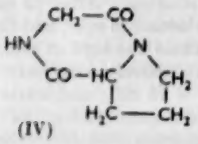
The principal product of the self-condensation of both glycylproline and prolylglycine ethyl esters was glycylproline anhydride (3 : 6-dioxo-1 : 2-pyrrolidinopiperazine) (IV), irrespective of whether the reaction was brought about by heating without solvent or by the action of ethanolic triethylamine. There was, however, a remarkable difference in the ease of cyclisation of the two esters, that from glycylproline undergoing this reaction very much faster than its isomeride, cyclisation being complete in a few hours at room temperature; as was to be expected there was no detectable difference between the self-condensation of the L- and the DL-esters to form the anhydride (IV) which contains only one asymmetric carbon atom. It is also noteworthy that, whereas the anhydride (IV) is the sole product of the self-condensation of glycylproline ethyl ester, it is accompanied in the case of prolylglycine ethyl ester by other products which, although not closely investigated, are almost certainly open-chain condensation polymers.

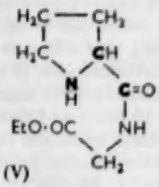
The greater ease of cyclisation of glycylproline ethyl ester as compared with prolylglycine ethyl ester is surprising, since the probable basic strengths of the amino- and imino-groups involved (pK_a between 7·6 and 8·4, and about 9·7, respectively [15]) are such that the latter ester might have been expected to be the more readily cyclised. Clearly this is a case in which geometrical and stereochemical factors take control; two such can be recognised. First, in prolylglycine ethyl ester the peptide linkage will presumably adopt the generally preferred *trans*-conformation [16] and energy will be required to convert this into the *cis*-conformation (V) necessary for cyclisation; no such reluctance to take up the necessary conformation (VI) is to be expected in the case of glycylproline ethyl ester. Secondly, in glycylproline ethyl ester four of the six atoms involved in the final piperazinedione ring are rigidly fixed by virtue of their occurrence in, or direct attachment to, the pyrrolidine ring, whereas only three atoms are so fixed in prolylglycine ethyl ester [atoms fixed in this way are shown in (V) and (VI) in heavy type]; this will result in a considerably greater probability of the molecule's taking up the conformation required for cyclisation in the case of glycylproline ethyl ester.

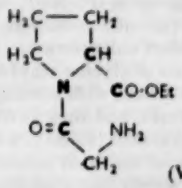
Very complex mixtures were obtained when the three tripeptide esters were heated alone or in ethanol, and only the cyclic products formed were isolated and identified. All

[15] Cohn and Edsall, "Proteins, Amino-acids and Peptides as Ions and Dipolar Ions," Reinhold, New York, 1943, Chapter 4.
[16] Corey and Pauling, *Proc. Roy. Soc.*, 1953, *B*, **141**, 10.

three esters gave glycylproline anhydride (IV), the yield of this product being higher from the esters of diglycylproline and glycylprolylglycine than from that of prolylglycylglycine. This is a further example of the similar degradation to piperazine-2 : 5-dione observed with polyglycine esters,[7] although the formation of the anhydride (IV) from diglycylproline ethyl ester shows that the reaction is not restricted to the amino-end of the molecule.


(IV)


(V)


(VI)

Piperazine-2 : 5-dione was also present in the products from diglycylproline and glycylprolylglycine ethyl esters; in the former case this product, too, can arise by the same degradative reaction but in the latter case it must be formed by dimerisation of glycine ethyl ester, produced as the other product in the cyclisation to the anhydride (IV). The lower yield of the anhydride (IV) obtained from prolylglycylglycine ethyl ester, as compared with its isomerides, is ascribed to the operation of the stereochemical factors considered to govern the cyclisation of the dipeptide esters.

The tetrapeptide ester, prolyldiglycylglycine ethyl ester (III; $m = 0$, $n = 3$, R′ = H, R′ = Et), resembled triglycylglycine ethyl ester [7] in being very resistant to self-condensation, both under the influence of heat and in ethanolic triethylamine.

Experimental

Preparations

M. p.s (uncorrected) were determined in a bath preheated to 15° below the m. p. The purity of all products was checked by paper chromatography.

DL-Proline was synthesised by Albertson and Fillman's method;[17] L-proline was isolated (13% yield) from gelatin by the rhodanilate method,[18] without prior removal of arginine.

Derivatives of Glycyl-DL-proline.—*N*-Benzyloxycarbonylglycine thiophenyl ester [19] (9·5 g.), in tetrahydrofuran (50 ml.), was treated with a solution of DL-proline hydrochloride (4·6 g.) in 2N-sodium hydroxide (31 ml.). After addition of methanol until homogeneous, the mixture was heated under reflux at 60—65° for 4 hr. The volatile solvents were then removed under reduced pressure and the residue, diluted with a little water, was extracted with ether to remove thiophenol. Acidification (1 : 1 hydrochloric acid; Congo-red) precipitated an oil (7·7 g., 80%) which rapidly crystallised when seeded; recrystallisation from ethyl acetate yielded *N*-benzyloxycarbonylglycyl-DL-proline as plates, m. p. 123° (Found: C, 59·3; H, 6·0. Calc. for $C_{15}H_{18}O_5N_2$: C, 58·8; H, 5·9%) (lit.,[9] m. p. 129—130°). Very much poorer yields (22%, 18%, and 7%, respectively) were obtained by the procedures of Bergmann and Fruton,[9] Boissonnas,[11] and Vaughan.[12]

This benzyloxycarbonyldipeptide (6 g.) was kept overnight in methanol (100 ml.) over Raney nickel (1 g.). After addition of water (2 ml.) and acetic acid (2 ml.) to the filtered solution the mixture was shaken in a current of hydrogen in the presence of palladium black [19] (0·35 g.). Evolution of carbon dioxide ceased after 3 hr., then the catalyst was removed by filtration; careful addition of ether then precipitated glycyl-DL-proline (3 g., 89%) as a slightly hygroscopic microcrystalline powder, m. p. 186° (decomp.) (Found: C, 48·4; H, 7·2; N, 16·7. Calc. for $C_7H_{12}O_3N_2$: C, 48·8; H, 7·0; N, 16·3%) (Bergmann and Fruton [9] do not record a m. p.).

The dipeptide (1·7 g.) was kept overnight in anhydrous ethanolic N-hydrogen chloride (11 ml.). The product was evaporated to dryness under reduced pressure and the whole procedure repeated twice. *Glycyl-DL-proline ethyl ester hydrochloride* (2·25 g., 96%), recrystallised from ethanol–ether, had m. p. 137° (decomp.) (Found: C, 46·25; H, 7·4. $C_9H_{17}O_3N_2Cl$ requires C, 45·7; H, 7·2%).

[17] Albertson and Fillman, *J. Amer. Chem. Soc.*, 1949, **71**, 2818.
[18] Bergmann, *J. Biol. Chem.*, 1955, **110**, 473.
[19] Willstätter and Waldschmidt-Leitz, *Ber.*, 1921, **54**, 123.

Derivatives of Glycyl-L-proline.—*N*-Benzyloxycarbonylglycyl-L-proline, prepared in 68% yield by condensing *N*-benzyloxycarbonylglycine thiophenyl ester with L-proline as described for the DL-compound, had m. p. 155° (lit.,[8] m. p. 156°); the procedures of Bergamnn *et al.*[8] and Boissonnas[11] gave inferior yields (37% and 20%, respectively). Hydrogenolysis gave glycyl-L-proline, m. p. 184° (lit.,[8] m. p. 185°), in 85% yield; esterification afforded the ethyl ester hydrochloride as a brittle gum which resisted all attempts at crystallisation.

Derivatives of DL-Prolylglycine.—*N*-Benzyloxycarbonyl-DL-proline[3] (9·0 g.), dissolved in dry chloroform (25 ml.) containing dry redistilled triethylamine (5 ml.), was cooled to 0° while redistilled ethyl chloroformate (3·5 ml.) was added rapidly with shaking. After 15 min. at 0°, a cold mixture of glycine ethyl ester hydrochloride (5·1 g.), triethylamine (5 ml.), and chloroform (25 ml.) was added, with stirring, to the semi-solid mass. The mixture was kept at room temperature for 30 min. and then at 50° for 10 min., and then washed successively with water (25 ml.), N-hydrochloric acid (15 ml.), 0·5N-sodium hydrogen carbonate (2 × 15 ml.), and water (15 ml.). Evaporation of the dried solution under reduced pressure afforded a gum (11·3 g., 94%), which crystallised slowly but completely (m. p. 54—56°); *N-benzyloxycarbonyl-DL-prolylglycine ethyl ester*, crystallised from ether–light petroleum (b. p. 40—60°), had m. p. 59—60° (Found: C, 61·1; H, 6·9. $C_{17}H_{22}O_5N_2$ requires C, 61·1; H, 6·6%).

This ester (8·2 g.) was kept at room temperature for an hour with N-sodium hydroxide (26 ml.) and acetone (10 ml.). Concentration, acidification, extraction with ethyl acetate, and evaporation of the dried extract gave an oil (6 g., 80%) which solidified (m. p. 123—124°) on being rubbed with ether; *N-benzyloxycarbonyl-DL-prolylglycine* crystallised from ethyl acetate in needles, m. p. 125° (Found: C, 58·75; H, 5·7. $C_{15}H_{18}O_5N_2$ requires C, 58·8; H, 5·9%). Hydrogenation of this derivative (3 g.), over palladium black (0·3 g.) in 50% aqueous methanol (100 ml.) containing acetic acid (1·5 ml.), yielded DL-prolylglycine (1·45 g., 86%), m. p. 223—224° (decomp.) (from aqueous methanol) (lit.,[8] m. p. 225—227°). Esterification as usual with ethanolic hydrogen chloride gave an 85% yield of *DL-prolylglycine ethyl ester hydrochloride*, hygroscopic needles, m. p. 95—96° (from ethanol–ether containing a little hydrogen chloride) (Found: C, 45·3; H, 7·3. $C_9H_{17}O_3N_2Cl$ requires C, 45·7; H, 7·2%).

Derivatives of L-Prolylglycine.—*N*-Benzyloxycarbonyl-L-proline, prepared in 90% yield by the procedure described by Abderhalden and Nienburg[3] for the DL-compound and recrystallised from ether–light petroleum (b. p. 40—60°), had m. p. 75° (Found: C, 62·6; H, 6·05. Calc. for $C_{13}H_{15}O_4N$: C, 62·7; H, 6·05%) (lit.,[20] m. p. 76—77°) and was converted, by the procedures described for the DL-compounds, into (i) *N*-benzyloxycarbonyl-L-prolylglycine ethyl ester (98% yield), an uncrystallisable oil, (ii) *N-benzyloxycarbonyl-L-prolylglycine* (65% yield), needles, m. p. 125° (from water) (Found: C, 59·2; H, 5·9. $C_{15}H_{18}O_5N_2$ requires C, 58·8; H, 5·9%) (described as a syrup by Abderhalden and Nienburg[3]), (iii) L-prolylglycine monohydrate (84% yield), m. p. 236° (decomp.), $[\alpha]_D^{17}$ −19·8° (*c* 4·0 in H_2O) (lit.,[3] m. p. 236°, $[\alpha]_D^{20}$ −22·8°), and (iv) *L-prolylglycine ethyl ester hydrochloride* (87% yield), hygroscopic needles, m. p. 119—120° (from ethanol–ether), $[\alpha]_D^{22}$ −39·5° (*c* 2·4 in H_2O) (Found: C, 45·8; H, 7·5. $C_9H_{17}O_3N_2Cl$ requires C, 45·7; H, 7·2%).

Derivatives of Diglycyl-L-proline.—*N*-Benzyloxycarbonylglycylglycine[21] (2·66 g.), in dry tetrahydrofuran (10 ml.) containing *N*-ethylpiperidine (1·4 ml.), was treated at 0° with ethyl chloroformate (1 ml.). After 15 min. at 0°, thiophenol (1 ml.) was added to the semisolid mass, which was then kept at room temperature for 4 hr. Base hydrochloride was then filtered off and washed with a little tetrahydrofuran. The solid product, obtained by evaporation of the filtrate and washings to dryness under reduced pressure, was recrystallised from benzene (100 ml.); *N-benzyloxycarbonylglycylglycine thiophenyl ester* (2·5 g., 70%) had m. p. 117° (Found: C, 60·7; H, 5·3. $C_{18}H_{18}O_4N_2S$ requires C, 60·3; H, 5·05%).

This ester (3·6 g.), in tetrahydrofuran (40 ml.), was treated with a solution of L-proline (1·15 g.) in N-sodium hydroxide (10 ml.) and heated under reflux to 65° for 4 hr. after homogenisation with methanol. Concentration under reduced pressure, removal of thiophenol by extraction with ether, and acidification precipitated an oil (3 g., 82%) which crystallised on being seeded; *N-benzyloxycarbonylglycylglycyl-L-proline* crystallised from ethyl acetate in short rods, m. p. 137° (Found: C, 56·4; H, 5·9. $C_{17}H_{21}O_6N_3$ requires C, 56·2; H, 5·8%). This compound (3·8 g.), in methanol (50 ml.), was kept overnight with Raney nickel (0·6 g.). Acetic acid (1·5 ml.) was added to the filtered solution which was then shaken in a current of hydrogen over palladium black[19] (0·17 g.); hydrogenolysis was complete in 2 hr. A little water was added to redissolve some product which had crystallised and the mixture was then filtered and

[20] Berger, Kurtz, and Katchalski, *J. Amer. Chem. Soc.*, 1954, **76**, 5552.
[21] Bergmann and Zervas, *Ber.*, 1932, **65**, 1192.

concentrated under reduced pressure to a syrup. Next morning methanol (80 ml.) was added and the first crop of product collected by filtration; re-concentration of the filtrate and further treatment with methanol gave a second crop. Diglycyl-L-proline (2·3 g., 96%) crystallised from aqueous ethanol as the *monohydrate*, large plates, m. p. 205—206° (decomp.), $[\alpha]_D^{23}$ −92·9° (*c* 2·1 in H_2O) (Found: C, 43·7; H, 7·1; N, 16·8. $C_9H_{15}O_4N_3,H_2O$ requires C, 43·8; H, 6·9; N, 17·0%) (E. L. Smith and Bergmann [4] record $[\alpha]_D^{26}$ −101·5° for a product analysing for a hemihydrate but do not give a m. p.). Esterification in the usual manner gave *diglycyl-L-proline ethyl ester hydrochloride* (87% yield), m. p. 112—114° (from ethanol–ether) (Found: C, 43·8; H, 6·6; N, 13·7. $C_{11}H_{20}O_4N_3Cl,0{\cdot}5H_2O$ requires C, 43·7; H, 6·95; N, 13·9%).

Derivatives of Glycyl-L-prolylglycine.—*N*-Benzyloxycarbonylglycine [21] (2·09 g.), in dry chloroform (10 ml.) containing triethylamine (1·35 ml.), was treated at 0° with ethyl chloroformate (1 ml.). After 10 min. a solution of L-prolylglycine ethyl ester hydrochloride (2·36 g.) in chloroform (10 ml.) containing triethylamine (1·35 ml.) was added. After 2 hr. at room temperature, the product was worked up in the usual manner, yielding *N*-benzyloxycarbonylglycyl-L-prolylglycine ethyl ester as an uncrystallisable oil (3·8 g., 90%); saponification of a portion gave *N*-benzyloxycarbonylglycyl-L-prolylglycine, m. p. 143—144° (from ethyl acetate) (Found: C, 55·9; H, 5·6. Calc. for $C_{17}H_{21}O_6N_3$: C, 56·2; H, 5·8%) (Simmonds and Fruton [22] give m. p. 136—137°; Davies and E. L. Smith [23] m. p. 144—145°).

The oily benzyloxycarbonyl-ester (3·37 g.) in ethanol (60 ml.) containing 10*N*-hydrochloric acid (1·5 ml.), was hydrogenolysed over palladium black [19] (0·2 g.). After an hour, water (20 ml.) was added to redissolve the precipitate and hydrogenolysis continued for a further hour. After filtration, the solution was evaporated to dryness under reduced pressure; the residue was taken up in ethanol and again evaporated, this process being then twice repeated. *Glycyl-L-prolylglycine ethyl ester hydrochloride* (2·25 g., 89%), recrystallised from ethanol, had m. p. 214° (decomp.), $[\alpha]_D^{23}$ −104·0° (*c* 1·52 in H_2O) (Found: C, 45·3; H, 6·9; N, 14·4. $C_{11}H_{20}O_4N_3Cl$ requires C, 45·0; H, 6·8; N, 14·3%).

Derivatives of Glycyl-DL-prolylglycine.—*N*-Benzyloxycarbonylglycyl-DL-prolylglycine ethyl ester was prepared as a gum (75—80% yield) by the procedure described for the L-compound and was converted by saponification into *N-benzyloxycarbonylglycyl-DL-prolylglycine* (70% yield), m. p. 133·5° (from ethyl acetate) (Found: C, 55·85; H, 6·15. $C_{17}H_{21}O_6N_3$ requires C, 56·2; H, 5·8%), hydrogenolysis of which gave *glycyl-DL-prolylglycine* (85% yield), which crystallised from aqueous methanol as the dihydrate, m. p. 245° (decomp.; previous sintering) (Found: C, 40·85; H, 7·15; N, 16·25. $C_9H_{15}O_4N_3,2H_2O$ requires C, 40·75; H, 7·2; N, 15·85%) (Davies and E. L. Smith [23] describe a sesquihydrate).

Hydrogenolysis of the gummy benzyloxycarbonyl-ester, as described for the L-compound, afforded *glycyl-DL-prolylglycine ethyl ester hydrochloride* (91% yield), m. p. 213° (decomp.) (from ethanol) (Found: C, 45·2; H, 6·6. $C_{11}H_{20}O_4N_3Cl$ requires C, 45·0; H, 6·8%).

Derivatives of L-Prolylglycylglycine.—*N*-Benzyloxycarbonyl-L-proline (8·6 g.) was treated as usual with ethyl chloroformate (3·3 ml.) in chloroform (25 ml.) containing triethylamine (4·7 ml.). Condensation of the resulting mixed anhydride with glycylglycine ethyl ester hydrochloride (6·8 g.) in chloroform (25 ml.) containing triethylamine (4·7 ml.) afforded *N-benzyloxycarbonyl-L-prolylglycylglycine ethyl ester* (11·8 g., 87%), which crystallised from chloroform–ether or water in needles, m. p. 120° (Found: C, 58·4; H, 6·5; N, 10·8. $C_{19}H_{25}O_6N_3$ requires C, 58·3; H, 6·4; N, 10·7%). This compound (1·95 g.) was hydrogenolysed over palladium black [19] (0·3 g.) in ethanol (75 ml.) containing 10*N*-hydrochloric acid (1 ml.). The product was dried by repeated dissolution in ethanol and evaporation under reduced pressure and finally precipitated from ethanol with anhydrous ether as a gum which solidified to a very hygroscopic solid when rubbed with ether. This ester hydrochloride (1·4 g.), in chloroform (10 ml.), was treated with 2*N*-ammonia in chloroform (3·5 ml.); filtration and evaporation of the filtrate under reduced pressure gave *L-prolylglycylglycine ethyl ester* (1·1 g., 86%), m. p. 109° after repeated precipitation from chloroform with light petroleum (b. p. 60—80°) (Found: C, 50·1; H, 7·4; N, 16·2. $C_{11}H_{19}O_4N_3$ requires C, 51·3; H, 7·4; N, 16·3%).

The benzyloxycarbonyl-tripeptide ester (2 g.), in ethanol (40 ml.), was treated with hydrazine hydrate (100%; 0·5 ml.). Next day, the solution was evaporated to dryness under reduced pressure and the residue treated with light petroleum (b. p. 60—80°). The gelatinous product (1·9 g., 96%) was recrystallised from chloroform–ether; *N-benzyloxycarbonyl-L-prolylglycylglycine hydrazide* so prepared had m. p. 117—118° (indefinite; opaque melt) (Found: C, 52·6, 52·65; H, 6·2, 6·15; N, 18·6. $C_{17}H_{23}O_5N_5,0{\cdot}5H_2O$ requires C, 52·85; H, 6·25; N, 18·15%). This

[22] Simmonds and Fruton, *J. Biol. Chem.*, 1948, **174**, 705.
[23] Davies and E. L. Smith, *ibid.*, 1953, **200**, 373.

hydrazide (3·8 g.), in ethanol (80 ml.) containing water (10 ml.) and 10N-hydrochloric acid (2 ml.), was hydrogenated for 5 hr. over palladium black (0·4 g.). The hydrazide hydrochloride, isolated by evaporation of the filtered solution, was converted into the free hydrazide by passage of a 10% aqueous solution through a column of De-acidite FF and elution with water; two crystallisations from ethanol afforded *L-prolylglycylglycine hydrazide*, m. p. 184—187° after decomp. at 135—140° (Found : N, 28·25. $C_9H_{17}O_3N_5$ requires N, 28·8%).

Derivatives of Triglycyl-L-proline.—*N*-Benzyloxycarbonylglycylglycine thiophenyl ester (3·6 g.), in tetrahydrofuran (40 ml.), was treated with glycyl-L-proline (1·7 g.) in N-sodium hydroxide (10 ml.); methanol was added until the mixture was homogeneous, then it was heated under reflux at 60—65° for 4 hr. Volatile solvents were removed under reduced pressure; the residue was extracted with ether, acidified, and finally evaporated to dryness under reduced pressure. Extraction with acetone afforded *N*-benzyloxycarbonylglycyldiglycyl-L-proline (4·2 g., 100%) as an uncrystallisable gum. Hydrogenolysis by the usual procedure afforded triglycyl-L-proline which crystallised from aqueous methanol as the *hemihydrate* (1·6 g., 54%), hexagonal plates, m. p. 246° (decomp.), $[\alpha]_D^{24}$ −78·5° (*c* 1·2 in H_2O) (Found : C, 45·05; H, 6·5; N, 19·1. $C_{11}H_{16}O_5N_4,0{\cdot}5H_2O$ requires C, 44·75; H, 6·45; N, 19·0%).

N-Benzyloxycarbonyldiglycylglycine [24] (3·2 g.), suspended in chloroform (100 ml.) containing triethylamine (1·35 ml.), was treated at 0° with ethyl chloroformate (1 ml.). The resulting solution was treated with L-proline ethyl ester hydrochloride (1·8 g.) in chloroform (20 ml.) containing triethylamine (1·35 ml.). Next day unchanged benzyloxycarbonyldiglycylglycine (1·3 g.) was filtered off and the filtrate worked up in the usual manner, giving *N*-benzyloxycarbonyltriglycyl-L-proline ethyl ester (2·8 g., 62%) as a gum. Hydrogenolysis in a N-solution of hydrogen bromide in acetic acid (20 ml.), followed by filtration and addition of ether, precipitated *triglycyl-L-proline ethyl ester hydrobromide* (0·4 g., 16%) which, after crystallisation from slightly aqueous ethanol and two recrystallisations from aqueous ethanol–ether, had m. p. 179—181° (decomp.), $[\alpha]_D^{25}$ −60·0° (*c* 2·2 in H_2O) (Found : C, 37·4; H, 5·8. $C_{13}H_{23}O_5N_4Br,H_2O$ requires C, 37·8; H, 6·1%). The same compound was obtained in 14% overall yield by a similar Boissonnas coupling of *N*-benzyloxycarbonylglycylglycylglycine and glycyl-L-proline ethyl ester, followed by hydrogenolysis.

Derivatives of Triglycyl-DL-proline.—*N*-Benzyloxycarbonylglycylglycine, coupled with glycyl-DL-proline ethyl ester hydrochloride by the usual Boissonnas procedure, afforded *N*-benzyloxycarbonyltriglycyl-DL-proline ethyl ester as an uncrystallisable gum (82% yield); hydrogenolysis in ethanol containing hydrobromic acid afforded *triglycyl-DL-proline ethyl ester hydrobromide* (43% yield), m. p. 241° (decomp.) after recrystallisation from aqueous ethanol–ether (Found : C, 39·4; H, 5·9; Br, 20·3. $C_{13}H_{23}O_5N_4Br$ requires C, 39·5; H, 5·8; Br, 20·25%).

Derivatives of L-Prolyldiglycylglycine.—*N*-Benzyloxycarbonyl-L-proline (5 g.), in chloroform (15 ml.) containing triethylamine (2·7 ml.), was treated at 0° with ethyl chloroformate (2 ml.). After 10 min., diglycylglycine ethyl ester hydrochloride (5·0 g.), suspended in chloroform (60 ml.) containing triethylamine (2·7 ml.), was added with shaking and the mixture kept at room temperature for 30 min. and then at 50° for 10 min. Working up as usual afforded *N-benzyloxycarbonyl-L-prolyldiglycylglycine ethyl ester* (8·6 g., 95%) which had m. p. 108—109° after recrystallisation from ethyl acetate (Found : C, 56·35; H, 6·4. $C_{21}H_{28}O_7N_4$ requires C, 56·25; H, 6·25%). Hydrogenolysis in ethanol containing hydrochloric acid gave *L-prolyldiglycylglycine ethyl ester hydrochloride* (82% yield), m. p. 188° (decomp.) after recrystallisation from ethanol, $[\alpha]_D^{24}$ −14·0° (*c* 1·7 in H_2O) (Found : C, 44·65; H, 6·6; N, 16·0. $C_{13}H_{23}O_5N_4Cl$ requires C, 44·5; H, 6·6; H, 16·0%); treatment with ammoniacal chloroform yielded the free *ester*, m. p. 161—162° after precipitation from chloroform with ether (Found : OEt, 14·0. $C_{13}H_{22}O_5N_4$ requires OEt, 14·3%).

Self-condensation experiments

Paper chromatography was carried out on Whatman No. 1 filter paper, usually with butan-1-ol–pyridine–water (65 : 35 : 65; upper phase); spots were located by spraying with ninhydrin (0·1% in butan-1-ol) and by the chlorine–starch–iodide method.[25]

Glycyl-L-proline Ethyl Ester.—The ester, liberated from the hydrochloride (1·2 g.) with a solution of ammonia in chloroform, solidified overnight in a vacuum-desiccator over phosphoric

[24] Bergmann, Zervas, and Fruton, *J. Biol. Chem.*, 1935, **111**, 225.
[25] Rydon and P. W. G. Smith, *Nature*, 1942, **169**, 922.

oxide. A sample of the solid yielded glycyl-L-proline anhydride, m. p. 213° after recrystallisation from ethanol (lit.,[4] m. p. 213°), R_F 0·55 (ninhydrin-negative; chlorine-positive). When heated at 105°/10^{-3} mm. for 15 hr. the crude solid (669 mg.) gave the same anhydride (370 mg., 46%), m. p. 213°, and no other detectable product, apart from traces of unchanged ester and a little glycyl-L-proline.

Glycyl-DL-proline ethyl ester, liberated from the hydrochloride (1·2 g.), behaved similarly to the L-compound, cyclising rapidly at room temperature and, when heated at 105°/10^{-3} mm. for 16 hr., giving only *glycyl-DL-proline anhydride* (DL-3 : 6-*dioxo*-1 : 2-*pyrrolidinopiperazine*) (680 mg., 85%), rhombs, m. p. 173° (from ethanol) (Found: C, 54·9; H, 6·5; N, 17·8. $C_7H_{10}O_2N_2$ requires C, 54·5; H, 6·5; N, 18·2%), R_F 0·55 (ninhydrin-negative; chlorine positive).

L-*Prolylglycine Ethyl Ester*.—(*a*) The free ester (579 mg.), liberated from the hydrochloride with ammonia in chloroform, was dried at room temperature at 10^{-3} mm. for 3 hr. and then heated at 105°/10^{-3} mm. for 15 hr. Crystallisation began after 2 hr. and a sublimate and an oily distillate collected on the neck of the reaction vessel. Trituration of the product (439 mg.) with ethanol afforded glycyl-L-proline anhydride (250 mg., 56%), m. p. 211—212° after recrystallisation from ethanol, R_F 0·55. Chromatography of the remainder showed the presence of some unchanged dipeptide ester (R_F 0·52) and four other products, two ninhydrin-positive (R_F 0·41 and 0·33) and two, present in only small amount, ninhydrin-negative and chlorine-positive (R_F 0·27 and 0·21).

(*b*) The ester (from 800 mg. of hydrochloride) was kept at room temperature in N-ethanolic triethylamine (10 ml.). Glycyl-L-proline anhydride (370 mg., 71%), m. p. 208—210°, was deposited over a period of two weeks. Chromatography did not reveal the presence of any ninhydrin-positive material in the supernatant liquid.

DL-*Prolylglycine Ethyl Ester*.—(*a*) The ester (689 mg.), heated at 105°/10^{-3} mm., gave a product (544 mg.) from which glycyl-DL-proline anhydride (350 mg., 70%), rhombs, m. p. 170—171° (from ethanol), R_F 0·55, was isolated; unchanged dipeptide ester (R_F 0·52) and two other ninhydrin-positive products (R_F 0·42 and 0·36) were also present.

(*b*) Self-condensation in N-ethanolic triethylamine afforded glycyl-DL-proline anhydride (75% yield), m. p. 170°; no ninhydrin-positive products were found in the mother-liquor.

Diglycyl-L-proline Ethyl Ester.—(*a*) The ester (708 mg.), heated at 105°/10^{-3} mm. for 15 hr., gave a glass (621 mg.), shown by paper chromatography to contain unchanged ester (R_F 0·37), glycyl-L-proline anhydride (R_F 0·51), and a series of ninhydrin-positive polymers (R_F 0·32, 0·27, 0·22, and 0·19).

(*b*) The ester (from 750 mg. of hydrochloride) was refluxed in ethanol (80 ml.) for 21 days. Chromatography showed the ester to be largely unchanged, although a small amount of polymer was present, together with glycyl-L-proline anhydride and piperazine-2 : 5-dione.

(*c*) The product from (*b*), freed from ethanol under reduced pressure, was heated at 100°, in a sealed tube, for 7 days in *m*-cresol (12 ml.). Removal of the solvent under reduced pressure in an atmosphere of nitrogen and treatment of the residue with ether precipitated piperazine-2 : 5-dione (20 mg.), decomp. 300° after recrystallisation from water, identified by paper chromatography. The ethereal solution was evaporated to dryness; treatment of the residue with cold ethanol afforded a little glycyl-L-proline anhydride (20 mg.), m. p. 205—208° after recrystallisation from ethanol. The mother-liquors contained unchanged tripeptide ester, more glycylproline anhydride and at least three ninhydrin-positive polymers of regularly decreasing R_F value.

Glycyl-L-prolylglycine Ethyl Ester.—The ester (793 mg.) was heated at 105°/10^{-3} mm. for 15 hr. Trituration of the product (612 mg.) with ethanol yielded glycyl-L-proline anhydride (120 mg., 25%), m. p. 212—213°. Chromatography of the remainder showed the presence of unchanged tripeptide ester (R_F 0·35) and several other ninhydrin-positive products (R_F 0·0—0·23), in addition to more anhydride.

Glycyl-DL-prolylglycine Ethyl Ester.—(*a*) Heated for 15 hr. at 100°/10^{-3} mm., this ester gave a mixture similar to that obtained from the L-compound, although less of the more soluble glycyl-DL-proline anhydride (*ca.* 10%), m. p. 170—171°, could be isolated.

(*b*) The ester (670 mg.) was refluxed in ethanol (15 ml.) for 8 days. On cooling, crystals (40 mg.) separated and were shown, by chromatography, to be a mixture of approximately equal amounts of piperazine-2 : 5-dione and glycyl-DL-proline anhydride. Evaporation of the mother-liquor to dryness and trituration of the residue with cold ethanol (3 ml.), afforded more glycyl-DL-proline anhydride (160 mg., 40%), m. p. 171—172° after recrystallisation from ethanol. Paper chromatography of the final mother-liquors showed them to contain a complex mixture of products, including unchanged tripeptide ester and glycyl-DL-proline anhydride; one product

gave a blue-violet spot with ninhydrin, characteristic of polyglycine esters, rather than the yellow, changing to blue-grey of esters containing proline, and may have been diglycylglycine ethyl ester, since it moved at the same rate as a marker spot of this compound.

L-*Prolylglycylglycine Ethyl Ester.*—The ester (964 mg.), heated at 105°/10^{-2} mm. for 15 hr., yielded a hard glass (892 mg.). Chromatography showed the presence of much unchanged tripeptide ester (R_F 0·47) and one other ninhydrin-positive material (R_F 0·33) and of glycyl-L-proline anhydride (R_F 0·59) and two other ninhydrin-negative, chlorine-positive products (R_F 0·40 and 0·27).

L-*Prolyldiglycylglycine Ethyl Ester.*—(*a*) The ester was recovered unchanged (m. p. 159—160°; OEt, 13·7%) after being heated at 95°/10^{-3} mm. for 20 hr.

(*b*) The ester hydrochloride (350 mg.) was refluxed for 10 days with triethylamine (2·7 ml.) in ethanol (200 ml.). Paper chromatography revealed no other product than unchanged ester.

We thank Mr. B. Manohin (Manchester) and Mr. F. H. Oliver (London) for the microanalyses.

College of Technology, University of Manchester, Manchester, 1.
Imperial College of Science and Technology, S. Kensington, London, S.W.7.

[*Received, May 18th,* 1956.]

---

703. *Possible f-Orbital Hybridization in Uranyl and Related Complexes.*

By C. A. Coulson and G. R. Lester.

A theoretical study is made of the possible modes of description of the bonds in certain uranyl and related complexes. If a partial sexicovalent character is desired for the uranyl–ligand bonds, then *f* electrons must be considered to take part in the bonding. A discussion of the sizes and energies of these *f* orbits shows that the 6*f* is much more effective than the 5*f* for this purpose. It is concluded that this sexicovalency is one element in the total description, with ionic contributions probably predominant. There are other alternative descriptions of the covalency, which do not involve use of *f* orbitals in the formation of hybrids; but although these probably play some part, it seems likely that they need to be supplemented with *f* hybrids.

It has been suggested that there may occur a characteristic arrangement of covalent bonds in certain complexes involving the actinide series of elements. This arrangement is illustrated by the uranyl nitrate complex, $UO_2(NO_3)_3^-$. Here the uranyl group may be thought of as representing the polar axis of a sphere, along the equatorial plane of which (or, perhaps, close to the equatorial plane) there lie six equivalent coplanar bonds to the oxygen atoms of the co-ordinated nitrate ions. Crystallographic data for this system have been reported by Hoard and Stroupe,[1] by Jander and Wendt,[2] and by Zachariasen.[3] The last has shown that among the various U–O bonds in a large series of molecular complexes there is a complete gradation from the short (or "primary") bonds typical of the uranyl ion whose length is 1·8—2·1 Å to the long (or "secondary") bonds typical of the equatorial ligands, where the length may be as great as 2·6—2·7 Å. It is on the basis of this gradual change that the description "bond" is here applied to the equatorial linkages.

Other evidence in favour of bond formation has recently been advanced by Glueckauf, McKay, and co-workers,[4–8] who made the suggestion that the peculiar nature of these equatorial bonds in compounds in solution might be due to *f*-orbital hybridization and

[1] Hoard and Stroupe, *Atomic Energy Project Report*, 1943, *A*, 1229.
[2] Jander and Wendt, *Z. anorg. Chem.*, 1949, **258**, 1.
[3] Zachariasen, *Acta Cryst.*, 1954, **7**, 795.
[4] McKay and Mathieson, *Trans. Faraday Soc.*, 1951, **47**, 428.
[5] Glueckauf, McKay, and Mathieson, *ibid.*, p. 437.
[6] Gardner, McKay, and Warren, *ibid.*, 1952, **48**, 997.
[7] Glueckauf, *Nature*, 1949, **163**, 414.
[8] Glueckauf and McKay, *ibid.*, 1950, **165**, 594.

partial covalency. However, Katzin [9] has objected to this interpretation on the grounds that there is insufficient evidence to distinguish these systems from other complexes which are usually admitted to be mainly ionic in character. Yet if the equatorial bonds are purely ionic, it is not easy to understand: (*a*) The very definite stereochemical distribution of the ligands, where the secondary oxygen atoms never seem to deviate by more than 0·5 Å from the mid-plane, and not infrequently lie in it. (*b*) The partition experiments by Glueckauf and McKay, which showed a strong tendency for the uranyl group to surround itself with six adjacent oxygen atoms, some of which may be nitrate oxygens and others water oxygens. It is a natural conclusion from this evidence that there is present at least some degree of covalent bonding, conferring particular stability on certain numbers of ligands and on certain valency angles.

Others beside Glueckauf and McKay have drawn attention to the possible role of *f* electrons in bonding. Thus Hugus [10] has described a way in which *f* electrons may be used in some of the higher oxidation states of iodine, tellurium, and antimony; and Scott [11] has also employed 4*f* orbitals in the descriptions of the iodine compounds IF_5 and IF_7. Further, Connick and Hugus [12] have used the greater stability of the 5*f* as compared with the 6*d* orbitals in the region of the Periodic Table above thorium and protactinium to suggest the intervention of 5*f* orbitals in the bonding of UO_3,UO_2^{2+} and some of the transuranic elements. R. J. Elliott,[13] from an analysis of the paramagnetic susceptibility of salts involving NpO_2^{2+} and PuO_2^{2+} ions in compounds isomorphous with sodium uranyl acetate $Na(UO_2)(OAc)_3$, has shown convincingly that the susceptibility is compatible with uranium 5*f* rather than 6*d* electrons, so that if the uranyl group is bonded by other than ionic forces, it must presumably be partly by means of *f* electrons. A similar discussion of the magnetic susceptibility of a series of 8-co-ordinated complexes of U(IV), which is close to the spin-only value, has been given by Sacconi,[14] who again is led to suppose that some of the electrons are in atomic and not molecular 5*f* orbitals, though a clear-cut decision between 6*d* and 5*f* does not seem possible. This argument has been criticized by Dawson,[15] who shows that an equally satisfactory interpretation can be obtained if $6d^2$ are involved in atomic orbitals and the 5*f* in bonding. Quite recently Eisenstein and Pryce [16] have reconsidered the paramagnetism of uranyl and neptunyl ions in great detail, and have shown that the so-called "high-frequency terms" in the susceptibility of an isolated UO_2^{2+} or NpO_2^{2+} group lead to a strong presumption of *f* electrons even in these bonds. We shall show later that if *f* electrons play a part in primary U–O bonds, they are even more likely to do so in secondary bonds.

There is yet other evidence from thermochemistry. Thus Kapustinskii and Baranova [17] have drawn attention to the large ΔH—of the order of 13 kcal.—involved in the bonding of each hydrated water molecule in $UO_2(NO_3)_x$, where $x = 2$ or 3 and in addition either 2 or 3 water molecules are tightly fastened to the complex. The greater ability of UO_2^{2+} as compared, for example, with Ba^{2+}, for holding water molecules, and the more specific nature of these forces in the case of UO_2^{2+}, have been stressed by Crandall.[18]

There are yet other arguments for the participation of 5*f* electrons in bonds. Thus Diamond, Street, and Seaborg,[19] from a very careful study of the elution behaviour of a series of actinides and lanthanides, have shown that in high concentrations of hydrochloric acid the actinides may form complex ions with chloride ions to a greater extent than do the lanthanides. To explain this additional stability a partial covalent character is ascribed to the bonding in the transuranic elements. Such bonding would appear to involve the 5*f* electrons, though these authors did not discuss the precise way in which

[9] Katzin, *Nature*, 1950, **166**, 605.
[10] Hugus, *J. Amer. Chem. Soc.*, 1952, **74**, 1076.
[11] Scott, *J. Chem. Phys.*, 1950, **18**, 1420.
[12] Connick and Hugus, *J. Amer. Chem. Soc.*, 1952, **74**, 6012.
[13] R. J. Elliott, *Phys. Rev.*, 1953, **89**, 659.
[14] Sacconi, *R. C. Accad. Lincei*, 1949, **6**, 639.
[15] Dawson, *Nucleonics*, 1952, **10**, 39.
[16] Eisenstein and Pryce, *Proc. Roy. Soc.*, 1955, *A*, **229**, 20.
[17] Kapustinskii and Baranova, *Izvest. Akad. Nauk S.S.S.R., Otdel. Khim. Nauk*, 1952, 1122.
[18] Crandall, *J. Chem. Phys.*, 1949, **17**, 602.
[19] Diamond, Street, and Seaborg, *J. Amer. Chem. Soc.*, 1954, **76**, 1461.

this would occur. They did, however, show (we shall return to this later) that the relative sizes of the 5*f* orbitals would be approximately suitable for this purpose.

It is clear from this survey that *f* covalency must be considered seriously.

It does not seem possible to settle this matter of *f* covalency by experiment. We propose, therefore, to discuss what is involved in the hypothesis; and to see whether, on the basis of conventional theories of the chemical bond, a satisfactory description of this kind of bonding can be given. Much of our discussion, while given with particular reference to the uranyl complexes, will of course apply to other possible situations in which *f* bonding may occur. Let us provisionally admit the experimental evidence as indicating some degree of sexicovalent co-ordination in the equatorial plane (see Fig. 1). It is at once clear that such a system of bonds cannot be described in conventional terms by invoking hybridization among the familiar *s*-, *p*-, and *d*-type atomic orbitals of uranium. Nor will *f* electrons alone be sufficient. We must look for hybrids in which some, or all, of the possible *s*, *p*, *d*, and *f* atomic orbitals participate.

There are two general reasons why we may expect an *f*-type contribution to a hybrid. They are associated with Pauling's criterion of the strength of a hybrid orbital, and with Maccoll and Mulliken's criterion of the overlapping power of a hybrid. It will be convenient to discuss them separately.

Pauling [20] has defined the strength of an orbital in terms of the angular dependence of its non-radial part, a similar radial factor in all the contributing atomic orbital wave functions being assumed (see later). Thus if we normalize the angular factors to 4π, the appropriate σ-type angular terms and strengths are as shown in the Table. This Table

Atomic orbital	*s*	*p*	*d*	*f*
Angular term	1	$\sqrt{3}\cos\theta$	$\sqrt{5}(3\cos^2\theta - 1)/2$	$\sqrt{7}(5\cos^3\theta - 3\cos\theta)/2$
Strength	1	$\sqrt{3} = 1{\cdot}732$	$\sqrt{5} = 2{\cdot}236$	$\sqrt{7} = 2{\cdot}646$

would lead us to suppose that *f* electrons were capable of stronger bonding than *s*, *p*, or *d*. Such a conclusion may seem to indicate that the strength criterion is not a completely satisfactory one; but it is likely to give indications of the true situation, and we shall use it shortly to compare the strengths of various possible hybrids of *s*, *p*, *d*, and *f*. As we may expect from the familiar case of *s*, *p*, and *d*, these hybrids may have strengths which are greater than that of any of their components.

The particular combinations of *s*, *p*, *d*, and *f* orbitals which may be allowed can be found by group-theoretical considerations of the kind discussed by Kimball.[21] Let us define * the 7 possible distinct normalized *f* orbitals in terms of their angular factors as follows :

$$\left.\begin{aligned} f_z &= \frac{\sqrt{7}}{2}(5\cos^3\theta - 3\cos\theta), \qquad f_{z(x+y)} = \sqrt{\frac{105}{4}}\sin^2\theta\cos\theta\cos 2\phi \\ f_x &= \sqrt{\frac{21}{8}}\sin\theta\,(5\cos^2\theta - 1)\cos\phi, f_{xyz} = \sqrt{\frac{105}{4}}\sin^2\theta\cos\theta\sin 2\phi \\ f_y &= \sqrt{\frac{21}{8}}\sin\theta\,(5\cos^2\theta - 1)\sin\phi, \quad f_+ = \sqrt{\frac{35}{8}}\sin^3\theta\cos 3\phi \\ f_- &= \sqrt{\frac{35}{8}}\sin^3\theta\sin 3\phi \end{aligned}\right\} \quad . \quad (1)$$

in which the *z*-direction coincides with the polar axis. Then if we consider the case of six equivalent directions around the central atom, all in the equatorial plane, and two equivalent directions along the polar axis, the group symmetry is D_{6h}, and the basic atomic orbitals fall into the following representations of this group :

Representation ...	a_{1g}	a_{2u}	b_{1u}	b_{2u}	e_{1g}	e_{2g}	e_{1u}	e_{2u}
Atomic orbitals ...	s, d_z	p_z, f_z	f_+	f_-	d_{xz}, d_{yz}	$d_{x^2-y^2}$, d_{xy}	p_x, p_y, f_x, f_y	$f_{z(x^2-y^2)}$, f_{xyz}

* f_+ and f_- are used as being more convenient to write than the conventional $2^{-\frac{1}{2}}\{f_3 \pm f_{-3}\}$.

[20] Pauling, " Nature of the Chemical Bond," Cornell Univ. Press, 1939, p. 78.

[21] Kimball, *J. Chem. Phys.*, 1940, **8**, 188.

Following Kimball's methods, we imagine six equivalent coplanar hybrid bond orbitals, denoted collectively by χ, directed along the equatorial directions. These may be used as a reducible representation of D_{6h}, with the following character system :

Group operation ...	E	C_2	$2C_3$	$2C_6$	$3C_2'$	$3C_2''$	iE	iC_2	$2iC_3$	$2iC_6$	$3iC_2'$	$3iC_2''$
$\Gamma(\chi)$	6	0	0	0	2	0	0	6	0	0	0	2

This implies that $\chi \subset a_{1g} + b_{1u} + e_{1u} + e_{2g}$. Since f_+ is the only atomic orbital of representation b_{1u}, it follows that f_+ must appear in these hybrids, if they are equivalent. This argument provides the necessary justification of our earlier assertion that f electrons are necessary if we want to preserve the old idea of bond orbitals.

Similar arguments to this have been given by Shirmazan and Dyatkina [22] though they did not consider our particular symmetry, D_{6h}; and by Fumi and Castellan [23] who showed that f electrons were necessary in most cases of six equivalent bonds, though again they did not consider D_{6h}. Previously Van Vleck [24] had shown that sp^3d^3f are needed with some, though not with all, types of 8-co-ordination. Certain other cases have been studied by Fumi.[25] In several of these structures f electrons could be used, though it may be possible to obtain the necessary hybrids without them.

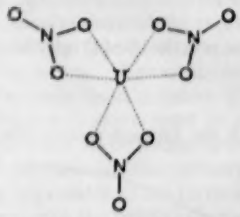


FIG. 1. *The equatorial " bonds " in uranyl nitrate.*

In many cases the X-ray analysis shows that in Fig. 1 the six equatorial bonds, although equivalent, are not at equal angles; but the angles between neighbouring bonds are alternately greater and less than 60°, as suggested by the fact that in the nitrate complexes adjacent pairs of attached oxygen atoms are bonded to a nitrogen atom. The symmetry is now D_{3h}, but an argument precisely equivalent to that used above for D_{6h} shows that again f_+ orbitals must be used.

The resolution of χ for the D_{6h} situation shows that the constituent atomic orbitals ψ_i ($i = 1 \ldots . 6$) must be of the form

$$\left.\begin{array}{lll} \psi_1 = s + c_1 d_z & , & \psi_4 = p_y + c_2 f_y \\ \psi_2 = f_+ & , & \psi_5 = d_{x+y} \\ \psi_3 = p_x + c_2 f_x & , & \psi_6 = d_{xy} \end{array}\right\} \quad . \quad . \quad . \quad (2)$$

where c_1 and c_2 are two arbitrary constants, and normalization factors have been omitted for convenience.

The definitions of the angular terms in the p and d functions are as follows :

$$\left.\begin{array}{lll} p_x = \sqrt{3}\sin\theta\cos\phi & , & d_{x+y} = \sqrt{\frac{15}{4}}\sin^2\theta\cos 2\phi \\ p_y = \sqrt{3}\sin\theta\sin\phi & , & d_{xy} = \sqrt{\frac{15}{4}}\sin^2\theta\sin 2\phi \\ d_z = \sqrt{5}(3\cos^2\theta - 1)/2 & , & d_{yz} = \sqrt{\frac{15}{4}}\sin\theta\cos\theta\sin\phi \\ & & d_{xz} = \sqrt{\frac{15}{4}}\sin\theta\cos\theta\cos\phi \end{array}\right\} \quad . \quad . \quad (3)$$

[22] Shirmazan and Dyatkina, *Zhur. fiz. Khim.*, 1953, **27**, 491.
[23] Fumi and Castellan, *J. Chem. Phys.*, 1950, **18**, 762.
[24] Van Vleck, *ibid.*, 1935, **3**, 803.
[25] Fumi, personal communication.

Presumably the least amount of *f*-type orbitals will occur if we are able to choose $c_2 = 0$. In general the total number of *f* electrons in the ψ_i amounts to $1 + 2c_2^2/(1 + c_2^2)^{\frac{1}{2}}$.

It is instructive to write the explicit relation between the atomic orbitals ψ_i in (2) and the resulting hybrid orbitals χ_i. The matrix relation between them may be written, symbolically

$$\boldsymbol{\chi} = \boldsymbol{T}\boldsymbol{\psi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where $\boldsymbol{\chi}$ is the column matrix χ_i, $\boldsymbol{\psi}$ is the column matrix ψ_i, and $\boldsymbol{T}$ is the square orthogonal matrix

$$\boldsymbol{T} = \begin{pmatrix} a & a & 2b & 0 & 2b & 0 \\ a & -a & b & \frac{1}{2} & -b & \frac{1}{2} \\ a & a & -b & \frac{1}{2} & -b & -\frac{1}{2} \\ a & -a & -2b & 0 & 2b & 0 \\ a & a & -b & -\frac{1}{2} & -b & \frac{1}{2} \\ a & -a & b & -\frac{1}{2} & -b & -\frac{1}{2} \end{pmatrix}$$

In the above expression for convenience we have put a for $1/\sqrt{6}$ and b for $1/\sqrt{12}$.

For example

$$\chi_1 = a(\psi_1 + \psi_2) + 2b(\psi_3 + \psi_5) \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The inverse relation to (4) may be put in the form

$$\boldsymbol{\psi} = \boldsymbol{T}^{-1}\boldsymbol{\chi} = \boldsymbol{T}^{\dagger}\boldsymbol{\chi} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where $\boldsymbol{T}^{\dagger}$ is the adjoint matrix obtained from $\boldsymbol{T}$ by interchanging rows and columns.

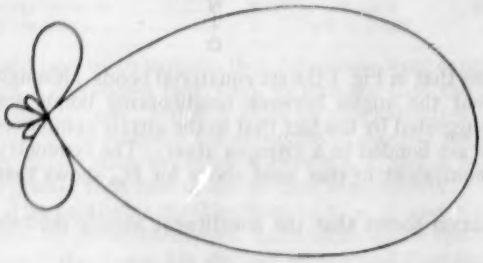


FIG. 2. *Polar diagram for spdf-hybrid. There are six of these, with coplanar axes of symmetry, arranged at 60° intervals in the equatorial plane.*

It is readily shown that the hybrids χ_i are of unusually high strength. For example if, in (2), we put $c_1 = c_2 = 0$, so that the hybrids are obtained from $s\ f_+\ p_x\ p_y\ d_{z+y}\ d_{xy}$, their strength, from eqns. (1) and (5), is $a\left(1 + \sqrt{\frac{35}{8}}\right) + 2b\left(\sqrt{3} + \sqrt{\frac{15}{4}}\right) = 3{\cdot}381$. This may be compared with the familiar sp^3 tetrahydral orbitals whose strength is 2·0. By making c_1 and c_2 in (2) very large so that the hybrids are derived from $d_z\ f_+\ f_x\ f_y\ d_{x+y}\ d_{xy}$ the strength becomes 3·364. An even bigger value can be found by suitable choice of c_1 and c_2; in fact, when $c_1 = \frac{\sqrt{5}}{2} = 1{\cdot}118$, $c_2 = \sqrt{\frac{7}{8}} = 0{\cdot}935$, we obtain the greatest possible strength, 3·954. Since, however, it is usually considered undesirable to introduce d_z and f_x orbitals if *s* and p_x can be used instead, it seems more reasonable to return to the first case, where the strength is still as great as 3·381. We show, in Fig. 2, the polar diagram for this particular hybrid. A comparison of this diagram with the conventional ones for sp^3 tetrahedral and other similar hybrids, shows how very strongly directed this hybrid is. Its overlapping power (see later), as expressed by overlap integrals between it and some ligand, is exceedingly large.

The last paragraph has been concerned with the case D_{6h} when all secondary O–U–O angles are 60°. It is not difficult to apply it to the D_{3h} situation. The chief alteration is that ψ_1 must be taken in the form $ns + \sqrt{(1 - n^2)}f_-$ instead of just *s*. Thus the ideal hexagonal configuration of hybrids results when $n = 1$. When $n \neq 1$, the total amount of *f* character in the hybrids is $2 - n^2$ (with $c_1 = c_2 = 0$ as urged above). This increases

with the angle subtended by adjacent bonds, for this angle depends on n according to the Table below.

n	1·00	0·90	0·75	0·50	0
Orbital strength	3·381	3·381	3·381	3·352	3·202
Bond angle	60°	50·6°	46·0°	42·2°	40°

The angle subtended by adjacent pairs of bonds may therefore be reduced from 60° to 46° without any appreciable reduction in the strength of the bond orbitals, though further increase in the *f*-orbital content causes the strength to fall more rapidly. It is interesting that the minimum possible angle that can be obtained in this way is 40°, so that if the actual angle is ever less than 40° it may be supposed that appreciable strain energy will occur, due to the inability of the various charge clouds to overlap effectively. Ionic Coulomb forces between the ligands are not likely to allow very small angles of this kind, and crystallographic data do, in fact, suggest a bond angle in the region of 46°. Presumably this value is largely determined by the bond distances and the shape of the attached groups, usually carbonate or nitrate.

So far no account has been taken of the axial bonds (primary U–O bonds) which lie normal to the equatorial plane. Their existence places certain restrictions on the possible types of in-plane hybridization, for the uranyl bonds will invoke some of the representations otherwise available for in-plane bonding. This is particularly true of the representations a_{1g} and a_{2u}, both of which may be used in σ-bonds along the z-axis. Eisenstein and Pryce [16] give reasons for supposing that these axial bonds may be made from uranium $5f_z$, $6d_z$, and $7s$ orbitals, though there may be a little $7p_z$ also. In such a case we must be careful not to put $c_1 = 0$ in eqn. (2) since then our various hybrids will not all be mutually orthogonal. Until we can be more explicit about the amount of hybridization in the primary bonds, it does not seem worthwhile to make detailed calculations, especially as we have shown that a small amount of mixing of s and d_z orbitals slightly increases the orbital strength.

This is about as far as it seems practicable to go by working in terms of Pauling's strength criterion. So let us now consider the overlap criterion of Maccoll [26] and Mulliken.[27] According to this, we may judge the bond-forming power of a hybrid by the magnitude of its overlap integral with the orbital on the ligand with which it is to be paired, and the smallness of its overlap with any other ligand.

The outer electrons in the ground state of uranium occupy the orbitals $(5s)^2$ $(5p)^6$ $(5d)^{10}$ $(6s)^2$ $(6p)^6$ $(5f)^3$ $(6d)$ $(7s)^2$. The precise self-consistent-field wave functions for these orbitals have not been calculated. We may therefore begin with Slater functions. In order to test the suitability of any or all of these orbitals for the polar and equatorial bonds we have calculated their overlap integrals with a hypothetical hydrogen 1*s* orbital placed $3{\cdot}3a_0$ and $4{\cdot}64a_0$ away. These are approximately the primary and secondary bond distances, if hydrogen atoms are replacing oxygen as ligands, and the overlap integrals thus calculated should give some general indication of the degree of overlapping of more accurate atomic orbitals with oxygen $2p\sigma$ orbitals. [After our calculations were complete, we realized that a rather smaller value of about $3{\cdot}0a_0$ instead of $3{\cdot}3a_0$ might have been better for the primary bond distance: but as our chief concern here is with the secondary bonds, for which $4{\cdot}64a_0$ is a reasonable value, we have not felt it was worthwhile to recalculate the overlap integrals shown in column (*a*) of the Table.] In order to make these integrations we had to use the Bessel-function technique developed by Barnett and Coulson.[28] The values in column (*b*) were obtained by direct integration in spheroidal co-ordinates for which, however, it is necessary that the power of r in the radial factor shall be integral. It was verified by accurate calculations for several of the six-quantum orbitals that the overlap integrals thus calculated with r^3 instead of the exact non-integral Slater powers of r (3·2 and 3·3) were not materially different from the exact values given in column (*a*). This less laborious procedure was therefore used in deriving the values in column (*b*). The orbitals, whose radial parts are shown in the Table, are only orthogonal as regards their

[26] Maccoll, *Trans. Faraday Soc.*, 1950, **46**, 369.
[27] Mulliken, *J. Amer. Chem. Soc.*, 1950, **72**, 4493.
[28] Barnett and Coulson, *Phil. Trans.*, 1951, *A*, **243**, 221.

angular dependence. It would have been possible to orthogonalize the orbitals of a given class (*e.g.*, *s*-type), but in view of the large difference in overlap between orbitals with differing principal quantum number, this process would hardly alter the final values; and as the Slater rules for the orbitals are themselves increasingly approximate for heavier atoms, further precision is not warranted. This Table shows that of the five-quantum

Overlap integrals between hydrogen 1s *and various uranium orbitals obtained by using Slater wave functions.*

Atomic orbital	Radial factor	Overlap integral (*a*)	(*b*)	Atomic orbital	Radial factor	Overlap integra (*a*)	(*b*)
5*s*	$1795r^4 \exp - 8{\cdot}59r$	0·041	—	$6d_{x^2-y^2}$	$1{\cdot}13r^{2\cdot2} \exp - 1{\cdot}74r$	0·345	0·199
5p_σ	$1795r^3 \exp - 8{\cdot}59r$	0·016	—	† 6d_z	$1{\cdot}13r^{2\cdot2} \exp - 1{\cdot}74r$	0·398	0·229
$5d_{x^2-y^2}$	$190r^3 \exp - 5{\cdot}21r$	0·021	—	6f_+	$0{\cdot}063r^{3\cdot2} \exp - 0{\cdot}94r$	0·231	0·296
5f_+	$28{\cdot}23r^4 \exp - 3{\cdot}41r$	0·041	—	† 6f_σ	$0{\cdot}063r^{3\cdot2} \exp - 0{\cdot}94r$	0·292	0·374
6*s*	$23{\cdot}68r^{3\cdot2} \exp - 3{\cdot}32r$	0·203	0·057	6f_σ	$0{\cdot}063r^{3\cdot2} \exp - 0{\cdot}94r$	0·179	0·229
6p_σ	$23{\cdot}68r^{3\cdot2} \exp - 3{\cdot}32r$	0·184	0·059	7*s*	$0{\cdot}00707r^{5\cdot2} \exp - 0{\cdot}62r$	0·203	0·249

(*a*) Internuclear distance = $3{\cdot}3a_0$. (*b*) Internuclear distance = $4{\cdot}64a_0$.
† Hydrogen orbital on the polar axis.

orbitals only the 5f_+ needs to be considered. Even then, its overlap is considerably less than either the 6*d* or 7*s*. If we agree to form the hexagonal hybrids as in eqn. (2) with $c_1 = c_2 = 0$, the overlap integral of one of the hybrids with its ligand hydrogen is as large as 0·486. This is much greater than its overlap with the remaining hydrogen atoms associated with the other hexagonal hybrids χ_2, χ_3, and χ_4 (*i.e.*, the unfavourable overlaps), for which the overlap integrals, in order, are —0·058, 0·019, and 0·082. The maximum overlap of 0·486 is rather less than the tetrahedral overlap in methane, where it is 0·701; but the other overlaps in methane are 0·157, suggesting that in this case the hexagonal hybrids have a more highly directional character, and are more suited to pairing with appropriate ligands, in the formation of localized bonds than are the tetrahedral hybrids in methane.

It is obvious that different choices of atomic orbital for the hybrids will lead to different sets of overlap integrals. In particular, it makes a difference whether 5f_+ or 6f_+ is used. But fortunately the general directional character of the hybrids does not appear to depend greatly on choices such as these. We have made a series of calculations of these overlaps, varying both the internuclear distance and the orbitals. In addition to the overlap of a hydrogen 1*s* with χ_1, χ_2, χ_3, and χ_4 quoted above (set 1 say) we give three other sets so that comparison may be made. These are, in order: set (2) 0·371, —0·059, 0·148, 0·062; set (3) 0·292, —0·138, 0·069, —0·017; and set (4) 0·469, —0·010, 0·099, —0·036. With our present knowledge there is no particular reason for rejecting any of these. Fortunately they are sufficiently similar in general behaviour.

Our ignorance may be put in another way, as follows. If, as we shall later be led to conclude, the true bonding is only partly of the covalent kind we are now considering, we have no grounds for deciding what exponents to use in the various atomic orbitals. This is because the total energy of the complex is determined not wholly by the overlap of the hybrids, but also by the valency-state energy, and the ionic energy, and by resonance between covalent and ionic wave functions. Fortunately again, the overlap integrals do not appear to be highly sensitive to the valency state selected. For example, instead of the set of atomic orbitals used in column (*a*) of the Table, we have considered overlaps where the least conceivable degree of excitation to a valency state is supposed to occur. The 6*s* overlap changes from 0·203 to 0·25, the 6*p* from 0·184 to 0·24, the 6*d* from 0·345 to 0·34. It does not seem, therefore, as if our ignorance of the particular nature of the valency state were in any real sense critical in our conclusions.

It is obvious from the Table of overlap integrals that the 6f_+ orbital is much more effective than the 5f_+ orbital. This situation raises several questions requiring answer. In the first place there is singularly little difference in energy between many possible levels of the uranium atom. For example the spectroscopic data of Kiess, Humphreys, and Laun [29] show that there exist a number of configurations where a 7*s* electron has been

[29] Kiess, Humphreys, and Laun, *J. Res. Nat. Bur. Stand.*, 1946, **37**, 57.

promoted to a 6*d* orbit, and which lie within 1 ev of the ground state. Further, De Bruin, Klinkenberg, and Schuurmans [30] have found a similar order of energy differences associated with the transition 6*d*–5*f* for thorium in its oxidation states. Moreover, theoretical estimates of the differences in energy between *f* electrons in various shells suggest (Wu [31]) that as little as 0·3 ev separates the 5*f* and 6*f* levels in uranium. Thus it would seem as if, on energy grounds, there were no really serious objection to using $6f_+$ orbitals in the secondary bond hybrids instead of $5f_+$. Part of our trouble is that, without adequate self-consistent-field orbitals, we are ignorant of the true sizes of the *f* orbitals. The situation here is more serious than with *s*, *p*, or *d* orbitals. For, as Goeppert-Mayer [32] has shown, there is a break in the slow change of size of a 5*f* orbital which occurs somewhere near $Z = 92$, such that for higher atomic numbers the 5*f* orbital is much smaller than before, and has its maximum density well within one Bohr radius of the nucleus. It is the existence of this break, which, by bringing the 5*f* electrons close to the nucleus, prevents them from affecting chemical properties of the atom, and leads to the existence of an actinide series. According to Seaborg it is between $Z = 90$ and $Z = 91$ that the 5*f* level crosses the 6*d* level and becomes the lower.

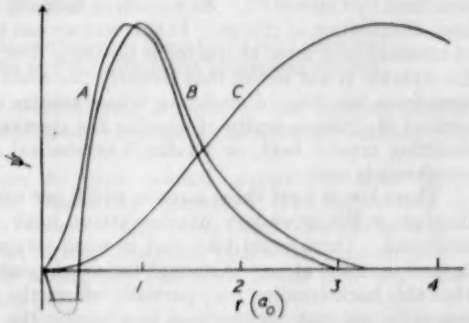


FIG. 3. *Radial part of* 5f *and* 6f *atomic orbitals for uranium* (A, *Slater* 5f; B, *Thomas–Fermi* 5f; C, *Slater* 6f *wave functions*).

It is certainly true that the Slater wave functions are likely to be particularly unreliable at these large atomic numbers. But Fig. 3 shows that, for our purposes, the error may be less than might have been expected. We have shown the variation with r of the radial part of the atomic orbital, both for the 5*f* and 6*f* Slater functions, and for the 5*f* function calculated by Eisenstein and Pryce [16] on the basis of a Thomas–Fermi statistical field in which the 5*f* electron moves. All these curves have been normalized in such a way that the peak value is 1·0. It is most gratifying that the Thomas–Fermi function agrees so closely with the Slater function. These curves show the greater overlapping power of the 6*f* as compared with the 5*f* orbital, in a striking fashion.

There is one other argument for preferring the 6*f* orbital. According to Fig. 3 this orbital appears rather too diffuse for maximum overlapping with the appropriate ligands: the 5*f* orbital, however, is too compressed. Now Craig [33] has shown, for the particular case of the *d* electron in transition-metal complexes, that the presence of electron-attracting groups surrounding the central ion results in an additional potential field acting on the outer electrons of this ion, and the effect of this field is to contract their charge clouds. The more diffuse the cloud was initially, the greater the relative contraction. As the Table of overlap integrals shows, the 6*f* is one of the most "outer" electrons in the uranium atom, and will therefore be contracted most in the co-ordinated state. It seems not unreasonable to suppose that if Fig. 3 gives the approximate size of the free-atom function, the co-ordinated-atom 6*f* function would be of about the right size for maximum overlapping.

We are now in a position to state our conclusions, even though these are to some extent still tentative. In the first place, if we believe that, in the secondary U–O bonds of

[30] De Bruin, Klinkenberg, and Schuurmans, *Z. Physik*, 1944, **122**, 23.
[31] Wu, *Phys. Rev.*, 1933, **44**, 727.
[32] Goeppert-Mayer, *ibid.*, 1941, **60**, 184.
[33] Craig, *Rev. Pure Appl. Chem.*, 1954, **4**, 4.

complexes such as the uranyl nitrates, there is some degree of simultaneous sexicovalent bonding, this can be achieved only with the help of *f* electrons. On the grounds of energy these could be either 5*f*, which are not particularly good since they do not overlap very strongly at the distances involved, or 6*f* which overlap much better. More probably, however, we may believe that such sexicovalent bonding is only one element in the complete account, and the ionic element is at least as important, or even more important. In this case the size and shape of the orbitals will be dominated by the ionic element, and there is no particular reason to suppose that any *f*-covalent character would need to be dependent exactly on isolated-atom 5*f* and 6*f* orbitals; probably all that we have any right so say is that there is some *f* character in the hybrids, and this *f* character will be such as to give best overlap with least expenditure of promotion energy. It is worth drawing attention to a situation which is not always as well recognized as it deserves to be (see, *e.g.*, Coulson [34]). If an electron is in the hybrid orbital shown in Fig. 2, its centre of mean position will lie somewhere near the centre of the large loop. This is already nearly half-way along the "bond" that is being formed, and it means that if we use this hybrid in what is formally a covalent bond, there will be a considerable dipole moment (due to the atomic dipole described by Coulson [35]). As a result, a formally covalent structure appears to have a large ionic distribution of charge. In this way we can begin to see that the conventional language of covalent and ionic character is breaking down. The situation here with *f* electrons in the hybrids is not unlike that recently discussed by Orgel,[36] for the octahedral and square complexes involving *d* electrons, where similar conclusions about spectral transitions are arrived at, independently of whether the starting point is Van Vleck's ionic model and the resulting crystal field, or Pauling's octahedral and square hybrids and the language of covalency is used.

There are at least three ways in which our earlier discussion could be modified. In the first place the secondary oxygen atoms have non-bonding (or almost non-bonding) π electrons. These could take part in weak π-type bonding, using the empty orbitals of the central uranium atom. Although the overlap integrals are not very large, it seems probable that this back-bonding may partially off-set the ionic character of the σ-type U–O bonds. Secondly, we may feel inclined to abandon the requirement of simultaneous sexicovalent bonding in the equatorial plane. Thus we could imagine resonance between a number of bond structures, in each of which only two, or four, bonds were drawn to the secondary oxygens. Resonance of this kind would be compatible with the hexagonal symmetry, and would require no use of *f* orbitals. It would be analogous to the way in which, in methane, the s^2p^2 bivalent state of carbon plays a fairly significant role, although it would appear to lead to bivalency and not quadrivalency. No doubt something of this sort occurs in uranium, though the larger energy difference in carbon (sp^3–s^2p^2 is about 4 ev) would tend to favour the lower valency in carbon more than in uranium, and in any case it is difficult to see how Eisenstein and Pryce's conclusions, that *f* electrons participate in the primary U–O bonds, could be fitted into this scheme. Thirdly, we may abandon the two-centre bond picture, and interpret the covalency, whether partial or complete, in terms of three-centre bonds, as is not infrequently done for the electron-deficient boron hydrides. Some recent work by W. C. Hamilton [37] shows that this is a useful method, even at a quantitative level. In such a case we should presumably use sd^2 hybrids at the uranium atom. These hybrids are equivalent and coplanar, but since both *s* and *d* are of gerade symmetry, so also are their mixtures; hence the three hybrids are directed not in three but in six directions, and the hexagonal arrangement could take place by the use of something like Rundle's half-bonds [38,39] without the need to use *f* electrons at all. This description can be regarded as a restricted type of resonance, though it has the great advantage of greater simplicity, and a more natural explanation for the existence of 6 rather than 4 ligands in the equatorial plane.

[34] Coulson, *Discuss. Faraday Soc.*, 1955, **19**, 65.
[35] *Idem*, *Trans. Faraday Soc.*, 1942, **38**, 433.
[36] Orgel, *J. Chem. Phys.*, 1955, **23**, 1004.
[37] Hamilton, *Proc. Roy. Soc.*, 1956, *A*, **235**, 395.
[38] Rundle, *J. Amer. Chem. Soc.*, 1947, **69**, 1327.
[39] *Idem*, *J. Chem. Phys.*, 1949, **17**, 671.

It is hard to avoid the conclusion that in heavy atoms, where there are many electrons in the same valency shell, or at comparable distances from the nucleus, the simple language that has been devised to account for bonding between light atoms is no longer applicable. There is—so it would appear—no uniquely compelling description, but rather there are several alternative descriptions which could be employed.

We should like to acknowledge the benefit of discussions with Dr. Glueckauf in the earlier stages of this investigation.

KING'S COLLEGE, LONDON.
[*Present addresses*: MATHEMATICAL INSTITUTE, OXFORD (C. A. C.).
IMPERIAL CHEMICAL INDUSTRIES LIMITED, HEXAGON HOUSE, BLACKLEY, MANCHESTER (G. R. L.).] [*Received, February 28th*, 1956.]

---

704. *The Structure of N_β-Alkyl-β-carboline Anhydro-bases.*

By IAN D. SPENSER.

The structures of N_β-alkyl-β-carboline anhydro-bases in the solid state and in solution are discussed in the light of their ultraviolet absorption spectra.

THE alkylation of β-carboline (I) and its *C*-substituted derivatives has been repeatedly studied [1-4] since 1919, when Perkin and Robinson recognised the alkaloid harmine (II) as the first member of this series.[5]

β-Carbolines react with alkyl iodides to give normal quaternary salts (III). With strong alkali these produce, not the quaternary hydroxides (IV), but yellow or orange anhydro-bases. Further alkylation of the anhydro-bases takes place at the indole-nitrogen atom, leading to salts (V) which on further treatment with alkali give the corresponding quaternary hydroxides, and when heated dry lose alkyl iodide from the basic nitrogen to give *ind-N*-alkylated β-carbolines (VI).[6,4]

The coloured anhydro-bases were originally formulated as (IX),[5] but are now regarded as resonance hybrids, with (IX) and (X) as the most important contributing structures.[7]

In recent years a number of alkaloids have been characterised as N_β-alkyl-β-carboline anhydro-bases, in which $C_{(1)}$ and N_β form part of a further ring.[8]

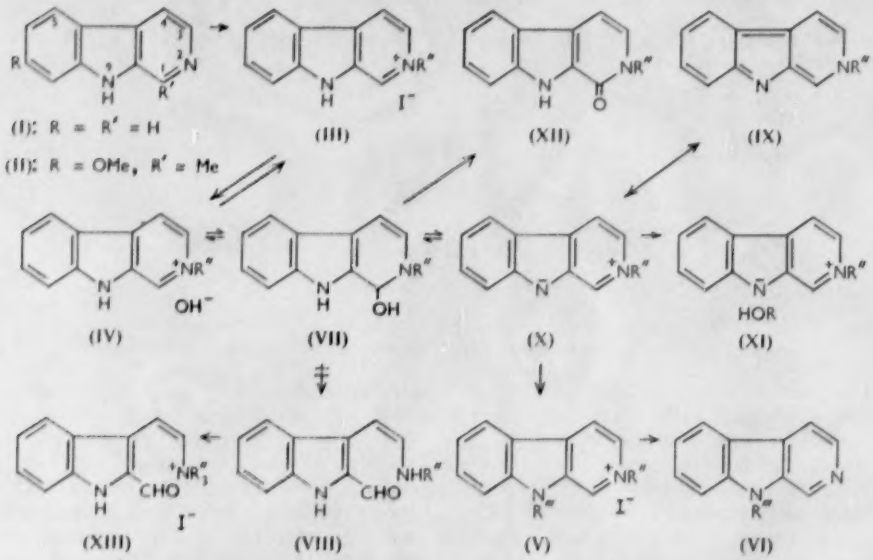
The anhydro-bases are all yellow or orange, their pK_a lie between 10 and 11, and they are soluble in polar and non-polar solvents, the latter solutions being in general darker than the former. They crystallise with solvent of crystallisation which is difficult to remove and tend to give unsatisfactory analyses.[9]

Like all anhydro- and *pseudo*-bases, the β-carboline anhydro-bases do not form salts of their own, but yield, with one mol. of acid, the faintly yellow quaternary salts (III) of the parent base. The infrared spectra of these salts (*e.g.*, sempervirine chloride [8a,10]) show an indole-NH band (2·9 μ) which is absent from the spectra of the anhydro-bases themselves. This is now confirmed by comparison of the infrared spectra of β-carboline methiodide and 2-methyl-β-carboline anhydro-base. (I thank Dr. S. F. D. Orr, Chester Beatty Research Institute, for the determination and interpretation of these spectra.)

The fact that further alkylation of the anhydro-bases takes place at the indole-nitrogen

[1] Kermack, Perkin, and Robinson, *J.*, 1922, **121**, 1872.
[2] Hasenfratz, *Ann. Chim.*, 1927, **7**, 151; Kermack and Slater, *J.*, 1928, 789; Konovalova and Orechov, *Arch. Pharm.*, 1934, **272**, 748; Leonard and Elderfield, *J. Org. Chem.*, 1942, **7**, 556.
[3] Speitel and Schlittler, *Helv. Chim. Acta*, 1949, **32**, 860.
[4] Cook, Loudon, and McCloskey, *J.*, 1951, 1203.
[5] Perkin and Robinson, *J.*, 1919, **115**, 933.
[6] Iyer and Robinson, *J.*, 1934, 1635.
[7] Armit and Robinson, *J.*, 1925, **127**, 1604.
[8] Woodward and Witkop, *J. Amer. Chem. Soc.*, 1949, **71**, 379; Elderfield and Grey, *J. Org. Chem.*, 1951, **16**, 506; Schlittler and Schwarz, *Helv. Chim. Acta*, 1950, **33**, 1463; Karrer and Schmid, *Angew. Chem.*, 1955, **67**, 361.
[9] Schwarz and Schlittler, *Helv. Chim. Acta*, 1951, **34**, 629.
[10] Witkop, *J. Amer. Chem. Soc.*, 1953, **75**, 3361.

atom is best interpreted by regarding the dipolar amphion (X) as the reacting form. If the compounds were of structure (IX), and not resonance hybrids, they should be diacidic, for in this formulation both nitrogen atoms would be basic. No instance of the addition to the anhydro-bases of two mols. of either acid or alkyl halide has been reported.



The ultraviolet spectra of the compounds confirm their anhydro-base character. In aqueous 0·1N-hydrochloric acid, the anhydro-bases give curve *B* of Fig. 1. Except for a bathochromic shift of 10 mμ, due to the introduction of an *N*-alkyl substituent into the chromophoric system, this curve is of the same shape as that given by β-carboline (I) in 0·1N-acid (curve *A*, Fig. 1). A slight further shift to longer wavelengths is found in the absorption of *ind*-*N*-alkylated quaternary β-carbolinium salts (V) (curve *C*, Fig. 1). The curves in Fig. 1 represent the absorption spectra of β-carbolinium ions (III, V) of increasing degree of nitrogen alkylation.

Aqueous or alcoholic solutions of β-carbolinium salts are only faintly yellow and exhibit a bright blue or blue-purple fluorescence.

An aqueous or alcoholic solution of the anhydro-bases yields the same curve (curve *B*, Fig. 1). This accords with the behaviour of all *pseudo*- and anhydro-bases so far studied, which in ionising solvents give ultraviolet spectra identical with those of their parent salts,[11] a measure of their readiness to revert, whenever possible, to the more stable salt structure.

In non-ionising solvents (*e.g.*, ether or chloroform), or in aqueous or alcoholic sodium hydroxide of pH >11·5, curve *D* of Fig. 2 is obtained. The same curve was also given by a solid film of 2-methyl-β-carboline anhydro-base, formed on a quartz slide by high-vacuum sublimation in the presence of phosphoric oxide. (I am indebted to Dr. J. E. S. Bradley, Middlesex Hospital Medical School, for this result.) Curve *D* is that of the free anhydro-base.

Fig. 3 shows the absorption spectra of the anhydro-base in aqueous or alcoholic ammonia or sodium hydroxide solutions of pH between 9·0 and 12·5. At pH values below 10·5, the curves obtained are identical with that given by the β-carbolinium ion (curve *B*, Fig. 1); the compound therefore exists as the quaternary ammonium hydroxide (IV). At pH values above 11·5, the absorption is that of the anhydro-base (curve *D*, Fig. 2). With

[11] Dobbie, Lauder, and Tinkler, *J.*, 1903, **83**, 598; Dobbie and Tinkler, *J.*, 1904, **85**, 1005; Steiner, *Bull. Soc. Chim. biol.*, 1924, **6**, 231; Bills and Noller, *J. Amer. Chem. Soc.*, 1948, **70**, 957.

increasing pH, at values between 10·5 and 11·5, the peaks due to the β-carbolinium ion at 255, 305, and 375 mμ gradually weaken in intensity and finally disappear, while the maxima due to the anhydro-base, at 275 and 325 mμ, appear as inflexions and increase finally to their full intensities. This indicates an equilibrium between quaternary hydroxide (IV) and anhydro-base, at pH values between 10·5 and 11·5.

FIG. 1. FIG. 3.

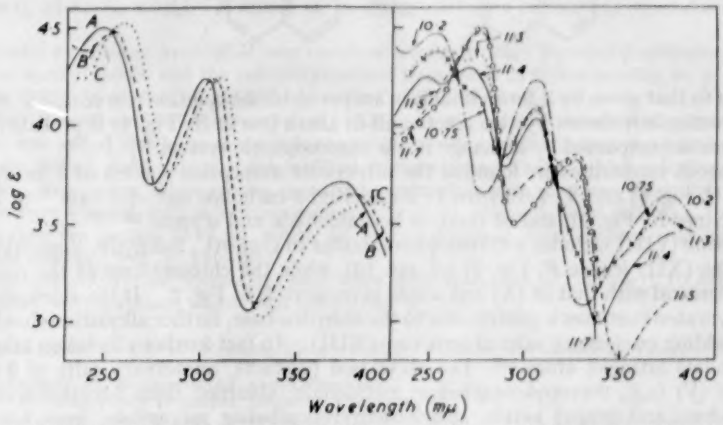


FIG. 1. *A, β-Carboline hydrochloride. B, β-Carboline methiodide. C, 9-Methyl-β-carboline propiodide. (All in* EtOH.)

FIG. 3. 1 : 2-*Dimethyl-β-carboline anhydro-base in aqueous solutions of* pH 9·5—11·7.

FIG. 2. FIG. 4.

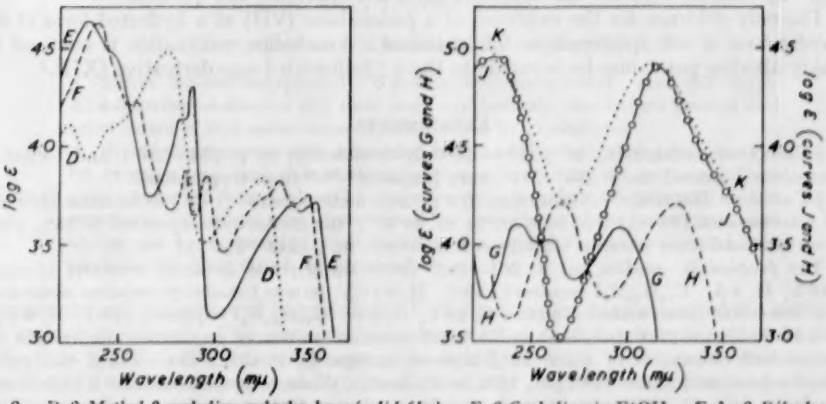


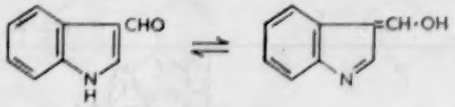
FIG. 2. *D, 2-Methyl-β-carboline anhydro-base (solid film). E, β-Carboline in* EtOH. *F,* 1 : 2-*Dihydro-2-methyl-1-oxo-β-carboline in* EtOH.

FIG. 4. 3-*Formylindole (G) in* EtOH *or* 0·1N-HCl *in aq.* EtOH; *(H) in* 0·1N-NaOH *in aq.* EtOH. *J,* 2-*Formylindole in* EtOH.[13] *K,* 3 : 4-*Dihydro-*1 : 2-*dimethyl-β-carboline anhydro-base in* $CHCl_3$ *or* 3 : 4-*dihydro-1-methyl-β-carboline methiodide in* 0·1N-NaOH *in aq.* EtOH.[14]

This interpretation is at variance with that of Schwarz and Schlittler,[9] who claim to have demonstrated an equilibrium between (IX) and (X). These structures are not tautomeric, however, but are canonical forms of a resonance hybrid and thus chemically and spectroscopically indistinguishable. From the observation that the anhydro-bases give curve *B* of Fig. 1 in aqueous or alcoholic solution, these authors conclude that in

ionising solvents the substances exist as pseudo-bases (VII) in equilibrium with amino-aldehyde (VIII), or as solvated molecules (XI).

None of the compounds (VII), (VIII), and (XI) would be likely to give a curve of type *B*. The *pseudo*-base (VII) can be considered as a 3-vinylindole, and although no ultraviolet spectrum of such a structure appears to have been published it would probably



be similar to that given by 3-formylindole in acid or alcoholic solution (curve *G*, Fig. 4). [The bathochromic shift shown by this compound in alkali (curve *H*, Fig. 4) is probably due to enolisation, accompanied by a change in the chromophoric system.[12]]

Analogous similarities are found of the ultraviolet absorption spectra of 2-formylindole (curve *J* [13], Fig. 4) and 3 : 4-dihydro-1 : 2-dimethyl-β-carboline anhydro-base [14] (a 2-vinylindole) (curve *K*, Fig. 4), and of those of benzaldehyde and styrene.[15]

Structure (VIII) includes a chromophore similar to that of 1 : 2-dihydro-2-methyl-1-oxo-β-carboline (XII) (curve *F*, Fig. 2) (cf. ref. 16), while the chromophore of the compound (XI) is identical with that of (X) and would give curve *D* of Fig. 2. If the aldehyde (VIII) were a hydrated tautomeric contributor to the anhydro-base, further alkylation should occur at N_β, yielding quaternary salts of structure (XIII). In fact further alkylation takes place at the indole nitrogen atom.[1-4] The alkylation products, quaternary salts of 9-alkyl-β-carboline (V) (*e.g.*, 9-propyl-β-carboline methiodide, obtained from 2-methyl-β-carboline anhydro-base and propyl iodide, and 9-methyl-β-carboline propiodide, from 2-propyl-β-carboline anhydro-base and methyl iodide) give β-carbolinium curves, identical in acid, neutral, and alkaline alcoholic solutions (curve *C*, Fig. 1), showing the shift to longer wavelengths, discussed above.

There is thus no evidence for the existence of an aldehyde-amine form (VIII), postulated [9] by analogy with the classical work on *N*-alkylpyridine and quinoline.[17]

The only evidence for the existence of a *pseudo*-base (VII) as a hydrated form of the anhydro-base is not spectroscopic but chemical : β-carboline methiodide is oxidised by weakly alkaline potassium ferricyanide to the 1 : 2-dihydro-1-oxo-derivative (XII).[1]

Experimental

β-Carboline (norharman), m. p. 198—200° (hydrochloride, m. p. 234—236°), and 1-methyl-β-carboline (harman), m. p. 235—237°, were prepared [8, 18, 19] from tryptophan.

β-Carboline Alkiodides.—Norharman (0·5 g.) and methyl iodide (1 ml.) in benzene (200 ml.) and nitrobenzene (20 ml.) was kept for 24 hr. at 37°; the methiodide separated in 95% yield. It recrystallised from water as slightly yellow prisms, m. p. 243—244° (cf. ref. 3).

The *propiodide*, needles, m. p. 201—202° (from water), was obtained similarly (Found : C, 49·5; H, 4·5. $C_{14}H_{15}N_2I$ requires C, 49·7; H, 4·5%); so was 1-*methyl-β-carboline methiodide*, m. p. 298—300° (from water) (Found : C, 48·1; H, 3·9. $C_{13}H_{13}N_2I$ requires C, 48·1; H, 4·0%).

2-Methyl-β-carboline Anhydro-base.[3]—A hot aqueous solution of β-carboline methiodide was treated with an excess of warm 20% aqueous sodium hydroxide. On cooling, the yellow anhydro-base, m. p. 212—214°, pK_a 10·6, crystallised. When recrystallised from a little water, a hydrate, m. p. 81—82°, was obtained; this loses water on further heating, and then resolidifies and remelts at 212—214°.

2-Propyl-β-carboline anhydro-base, m. p. 179—180°, pK_a 10·6, was obtained similarly from

[12] Cf. Majima and Kotake, *Ber.*, 1925, **58**, 2037; Baker and Happold, *Biochem. J.*, 1940, **34**, 657.
[13] Taylor, *Helv. Chim. Acta*, 1950, **33**, 164.
[14] Spenser, unpublished result.
[15] Gillam and Stern, "An Introduction to Electronic Absorption Spectroscopy in Organic Chemistry," Edward Arnold Ltd., London, 1954, p. 126.
[16] Johnson, Larsen, Holley, and Gerzon, *J. Amer. Chem. Soc.*, 1947, **69**, 2364.
[17] Hantzsch and Kalb, *Ber.*, 1899, **32**, 3109; Kaufmann and Strübin, *Ber.*, 1911, **44**, 680.
[18] Jacobs and Craig, *J. Biol. Chem.*, 1936, **113**, 759.
[19] Harvey, Miller, and Robson, *J.*, 1941, 153.

β-carboline propiodide. Recrystallisation from water gives a hydrate, m. p. 75—80°, which on further heating resolidifies and remelts at 179—180°.

1 : 2-Dimethyl-β-carboline anhydro-base, greenish-yellow needles,[18] m. p. 184—185°, pK_a 10·6, was obtained in the same way from harman methiodide.

9-Propyl-β-carboline Methiodide.—2-Methyl-β-carboline anhydro-base, in benzene, was treated with excess of propyl iodide and kept at 37° for 48 hr.; the *salt* crystallised; it recrystallised from water as yellow needles, m. p. 238—239° (Found: C, 51·2; H, 5·0. $C_{15}H_{17}N_2I$ requires C, 51·1; H, 4·9%). A mixed m. p. with β-carboline methiodide showed a depression of 30°.

9-Methyl-β-carboline propiodide was obtained similarly from 2-propyl-β-carboline anhydro-base and methyl iodide and the *salt* recrystallised from water as yellow needles, m. p. 262—263° (Found: C, 51·3; H, 5·1. $C_{15}H_{17}N_2I$ requires C, 51·1; H, 4·9%).

1 : 2-*Dihydro*-2-*methyl*-1-*oxo*-β-*carboline* [1] (XII).—A 4% aqueous solution of potassium ferricyanide was added slowly to a hot solution of β-carboline methiodide (0·9 g.) and potassium carbonate (2·0 g.), until a drop of the acidified mixture gave a Prussian-blue colour with ferrous sulphate. The warm solution was repeatedly extracted with benzene, and the combined extracts were washed with N-hydrochloric acid (2 × 20 ml.) and dried (KOH). Removal of solvent gave the lactam (0·12 g.), which on recrystallisation from ethanol was obtained in colourless needles,[1,16] m. p. 261—263°.

Ultraviolet Absorption Spectra.—These were determined on a Unicam S.P. 500 spectrophotometer, with solutions which were 5·0 (±0·5) × 10^{-5}M.

I am indebted to Dr. W. Robson, King's College, London, for advice and encouragement.

Department of Biochemistry and Chemistry,
St. Bartholomew's Hospital Medical College,
Charterhouse Square, London, E.C.1.

[*Received, March 7th,* 1956.]

---

705. *Synthesis of Heterocyclic Compounds from δ-Unsaturated* 1 : 3-*Diketo-esters.*

By Gabra Soliman and Latif Rateb.

Ethyl 6-*o*-methoxyphenyl-, 6-*p*-dimethylaminophenyl-, and 6-2′-furyl-2 : 4-dioxohex-5-enoates (II) have been synthesised; the known methyl and ethyl esters of this series were interconverted by alcoholysis.

Six of these esters were converted into 2 : 6-disubstituted 4-pyrones (V) on bromination, and dehydrobromination with potassium acetate. They were converted into 1-phenyl-5-styrylpyrazole-3-carboxylic esters (VI), the structures of which were determined by ozonolysis, decarboxylation, and hydrolysis to 1-phenylpyrazole-3-carboxylic acid. 3 : 5-Disubstituted *iso*-oxazoles (X) have also been prepared.

Syntheses and properties of δ-unsaturated 1 : 3-diketo-esters have attracted the attention of various chemists.[1] The aromatic prototype, ethyl 2 : 4-dioxo-6-phenylhex-5-enoate (II; R = Et, R′ = Ph) was first prepared by Schiff and Gigli [2] and later by Ruhemann.[3] Similarly, Ryan and Algar,[4] and Ryan and Plunkett,[5] prepared other hexenoates by the action of sodium on methyl oxalate and substituted methyl styryl ketones (I).

The present investigation involves the synthesis of ethyl 6-*o*-methoxyphenyl-, 6-*p*-dimethylaminophenyl-, and 6-2′-furyl-2 : 4-dioxohex-5-enoates (II) as well as interconversion of the methyl and ethyl esters by alcoholysis. These esters were obtained as described in the Experimental section in good yields unobtainable otherwise. Condensation of *p*-dimethylaminostyryl methyl ketone gave the desired ester and a high-melting

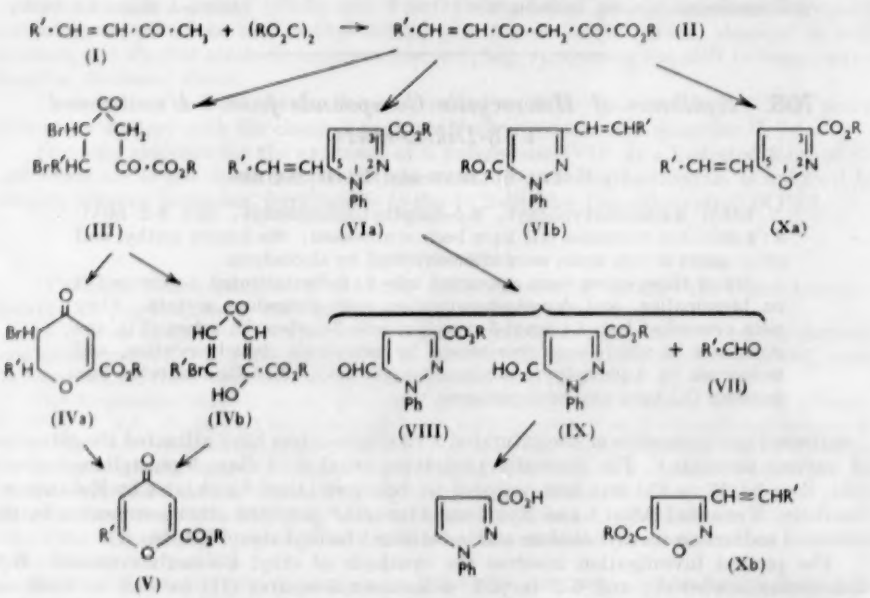
[1] *E.g.*, Claisen, *Annalen*, 1896, **291**, 119.
[2] Schiff and Gigli, *Ber.*, 1898, **31**, 1306.
[3] Ruhemann, *J.*, 1909, **95**, 109.
[4] Ryan and Algar, *Proc. Roy. Irish Acad.*, 1913, **32**, 9.
[5] Ryan and Plunkett, *ibid.*, 1916, **33**, 199.

product of undetermined structure; ethyl 6-*p*-dimethylaminophenyl-2 : 4-dioxohex-5-enoate readily loses its red colour in hydrochloric acid owing to engagement of the unshared electrons on the nitrogen by the hydrogen ion of the acid, resonance being thus prohibited.

We have utilised these esters in the synthesis of five new 6-aryl-4-pyrone-2-carboxylic esters (V), 1 : 3 : 5-trisubstituted pyrazoles (VI) and 3 : 5-disubstituted *iso*oxazoles (Xa or b), likely to be of medicinal importance.

Attempts to obtain the dibromides of these esters by the methods described by Ryan and Algar [4] and by Borsche and Peter [6] for (III; R = Me, R′ = *p*-MeO·C_6H_4) and (III; R = Et, R′ = Ph), respectively, gave unsatisfactory results. However, they were prepared as described in the Experimental section and were converted into 6-aryl-4-pyrone-2-carboxylic esters by the action of potassium acetate in presence of calcium carbonate. In absence of the latter reagent, transesterification occurred in an alcohol different from that associated with the alkoxycarbonyl group of the dibromide used. There is no doubt about the constitution of these pyrones, since ethyl 6-phenyl-4-pyrone-2-carboxylate was converted into 2-phenyl-1 : 4-pyrone on acid hydrolysis and decarboxylation; [6] they were characterised as picrates and on fission gave the expected acidic and ketonic products.

Apparently, dehydrobromination with potassium acetate does not give an acetylenic 1 : 3-diketo-ester. Otherwise, the formation of these pyrones would proceed by addition of the enolate group to the acetylenic bond.[7] Instead, stepwise elimination of hydrogen bromide leads to either a bromodihydro-4-pyrone (IVa) before dehydrogenation, or a bromo-olefinic ester (IV*b*) before cyclisation. The second alternative has experimental support in the work of Wislicenus [8] and Abell [9] who obtained ω-benzylidene-ω-bromoacetophenone by the action of potassium acetate on benzylideneacetophenone dibromide.



With phenylhydrazine the unsaturated 1 : 3-diketo-esters (II) gave the pyrazoles (VIa) and, again, transesterification was inevitable in acidic media. That these trisubstituted pyrazoles were obtained pure from the reaction medium is evidence that only one carbonyl

[6] Borsche and Peter, *Annalen*, 1927, **453**, 148.
[7] Soliman and El-Kholy, *J.*, 1954, 1755.
[8] Wislicenus, *Annalen*, 1899, **308**, 219.
[9] Abell, *J.*, 1912, **101**, 998.

group is involved in the primary condensation, which gave the ester (VIa) and not (VIb) since ozonolysis gave the aromatic aldehydes (VII), the aldehydic ester (VIII), and the monoester of 1-phenylpyrazole-3 : 5-dicarboxylic acid (IX), whose identity was established by hydrolysis to the free dicarboxylic acid.[10, 11] The 5 position assigned to the free carboxylic group is confirmed by ready decarboxylation of the half-ester (IX) to a neutral ester which was hydrolysed to 1-phenylpyrazole-3-carboxylic acid.[10]

Analogously, the 3 : 5-disubstituted *iso*oxazoles which have been prepared may be assigned the formula (Xa) [rather than (Xb)] in agreement with Musante's [12] suggestion for ethyl 5-styryl*iso*oxazole-3-carboxylate.

Experimental

Light petroleum used had b. p. 60—80°.

Ethyl 2 : 4-Dioxo-6-phenylhex-5-enoate.—Methyl styryl ketone (10 g., 1 mol.) and ethyl oxalate (10 g., 1 mol.) were added to an ice-cold suspension of sodium ethoxide (4·4 g., 1 mol.) in dry ether (100 ml.). The mixture was kept overnight at room temperature and the sodium salt was separated and acidified with 10% sulphuric acid. The recovered ester (14·8 g.) crystallised from ethanol in yellow needles, m. p. 84°, which gave a red colour with ferric chloride.

Methyl 2 : 4-dioxo-6-phenylhex-5-enoate was obtained when the ethyl ester (1 g.) was refluxed in methanol (5 ml.) containing one drop of concentrated sulphuric acid for 1 hr. It crystallised from methanol in yellow needles, m. p. 70°.

Both esters gave with 5% aqueous titanium trichloride [13] a blackish-brown colour which changed into bluish ⟶ violet ⟶ colourless.

Ethyl 5 : 6-Dibromo-2 : 4-dioxo-6-phenylhexanoate.—This was obtained quantitatively when an ice-cold 10% solution (65 ml.) of bromine in carbon disulphide was added to ethyl 2 : 4-dioxo-6-phenylhex-5-enoate (10 g.) in cold carbon disulphide (50 ml.). The mixture was kept cool overnight; the dibromide recovered by evaporation of the solvent at room temperature crystallised from ethanol in pale yellow needles, m. p. 107°.[6]

Ethyl 6-Phenyl-4-pyrone-2-carboxylate.—The foregoing dibromide (5 g.), fused potassium acetate (5 g.), calcium carbonate (5 g.), and absolute ethanol (30 ml.) were heated at 60—70° for 3 hr. The pyrone (1·8 g.) was recovered after concentration of the alcoholic solution, dilution with water, and extraction with ether. It crystallised from water in needles, m. p. 119° (Found: C, 68·6; H, 5·2. Calc. for $C_{14}H_{12}O_4$: C, 68·9; H, 5·0%). The *picrate* was prepared in alcohol and crystallised from alcohol in yellow needles, m. p. 130° (Found: N, 8·9. $C_{20}H_{15}O_{11}N_3$ requires N, 8·9%).

Methyl 6-phenyl-4-pyrone-2-carboxylate was obtained when ethyl 5 : 6-dibromo-2 : 4-dioxo-6-phenylhexanoate (3 g.) was heated with fused potassium acetate (3 g.) in absolute methanol (25 ml.) for 5 hr. The pyrone was recovered as above and crystallised from boiling water in plates, m. p. 127° (Found: C, 68·1; H, 4·2; OMe, 13·4. $C_{13}H_{10}O_4$ requires C, 67·8; H, 4·4; OMe, 13·5%). The two esters yielded 6-phenyl-4-pyrone-2-carboxylic acid,[6] m. p. 233°, when boiled with concentrated hydrochloric acid; this crystallised from water in needles, m. p. 238°.

Fission of the Pyrone.—Ethyl 6-phenyl-4-pyrone-2-carboxylate (0·5 g.) was refluxed with 20% aqueous potassium hydroxide (10 ml.) in an all-glass apparatus for 20 min. The mixture was then steam-distilled and the first 10 ml. of the ketonic distillate were collected separately. Subsequently, the alkaline mixture was acidified with 10% hydrochloric acid and steam-distilled. The first ketonic distillate gave a positive test for acetone, and the main ketonic distillate contained acetophenone.[7] The acidic distillate yielded 0·2 g. of benzoic acid and gave a positive test for acetic acid. The non-volatile residue was neutralised with aqueous ammonia and mixed with calcium chloride solution, and the precipitate obtained was identified as calcium oxalate by the aniline-blue test.[14]

Ethyl 1-Phenyl-5-styrylpyrazole-3-carboxylate.—This was prepared when a solution of the above ethyl hexenoate (2 g.) in ethanol (10 ml.) was refluxed with phenylhydrazine hydrochloride (1 g.) and sodium acetate (0·8 g.) in water (3 ml.) for 1 hr. It crystallised from ethanol in needles, m. p. 120°.

[10] Claisen, *Ber.*, 1891, **24**, 1888.
[11] Keskin, *Rev. Fac. Sci. Univ. Istanbul*, 1944, **9**, *A*, 81.
[12] Musante, *Gazzetta*, 1942, **72**, 134.
[13] Weygand and Caendes, *Chem. Ber.*, 1952, **85**, 45.
[14] Vogel, "Qualitative Chemical Analysis," Longmans, Green and Co., 1951, p. 311.

A chloroform solution of the ester (2 g.) was treated with ozonised oxygen, and after removal of the solvent, the ozonide was decomposed and distilled with steam until benzaldehyde ceased to pass over. The non-volatile residue was extracted with ether, and the ethereal solution shaken with sodium hydrogen carbonate solution. *Ethyl 5-formyl-1-phenylpyrazole-3-carboxylate* (VIII) (0·8 g.) was recovered from the neutral ethereal solution and crystallised from light petroleum in needles, m. p. 89° (Found: C, 63·9; H, 4·8; N, 11·4. $C_{13}H_{12}O_3N_2$ requires C, 63·9; H, 4·95; N, 11·5%). Its *oxime* crystallised from benzene–light petroleum in needles, m. p. 154° (Found: C, 60·2; H, 5·2; N, 16·2. $C_{13}H_{13}O_3N_3$ requires C, 60·2; H, 5·05; N, 16·2%).

3-Ethoxycarbonyl-1-phenylpyrazole-5-carboxylic acid (IX) (0·6 g.) was recovered from the sodium hydrogen carbonate extract and crystallised from benzene in needles, m. p. 164° (Found: C, 59·6; H, 4·9; N, 10·4. $C_{13}H_{12}O_4N_2$ requires C, 60·0; H, 4·65; N, 10·8%). It was also obtained by oxidation of the above aldehyde (VIII) with powdered potassium permanganate in acetone.

1-Phenylpyrazole-3 : 5-dicarboxylic Acid.—This acid [11] was obtained by hydrolysis of the foregoing monoester (0·1 g.) in boiling dilute hydrochloric acid (1 : 1) (4 ml.) for 1 hr., and crystallised from water in needles, m. p. 266°.

1-Phenylpyrazole-3-carboxylic Acid.—3-Ethoxycarbonyl-1-phenylpyrazole-5-carboxylic acid (0·4 g.) was decarboxylated at 180—185°. The oily residue was shaken in ether with sodium hydrogen carbonate solution. The ester recovered from the ethereal solution was hydrolysed by boiling with hydrochloric acid (1 : 1) (10 ml.) for 1 hr. The acid, m. p. 137°, which separated on cooling, crystallised from water in needles, m. p. 143° (Found: C, 63·5; H, 4·1. Calc. for $C_{10}H_8O_2N_2$: C, 63·8; H, 4·3%). Its methyl ester, prepared by diazomethane, crystallised from light petroleum in prisms, m. p. 72° (Found: C, 65·2; H, 5·0. Calc. for $C_{11}H_{10}O_2N_2$: C, 65·3; H, 5·0%).

Ethyl 5-Styrylisooxazole-3-carboxylate.—This was prepared when the above ethyl hexenoate (2 g.) in ethanol (20 ml.) was refluxed with hydroxylamine hydrochloride (0·7 g.) and sodium acetate (0·8 g.) in water (3 ml.) for 2 hr. It crystallised from ethanol in needles, m. p. 112°. The methyl ester, m. p. 143°, was obtained in a methanolic medium in absence of sodium acetate.

Ethyl 6-p-Methoxyphenyl-2 : 4-dioxohex-5-enoate.—This *ester* was prepared in 90% yield from 4-methoxystyryl methyl ketone and crystallised from ethanol in yellow needles, m. p. 92° (Found: C, 65·2; H, 5·9. $C_{15}H_{16}O_5$ requires C, 65·2; H, 5·8%). It gave a reddish-brown colour with ferric chloride and a reddish-brown colour which changed to brown ⟶ bluish ⟶ colourless with titanium trichloride. It gave on methanolysis the methyl ester which crystallised from methanol in yellow needles, m. p. 128°.

Methyl 5 : 6-Dibromo-6-p-methoxyphenyl-2 : 4-dioxohexanoate.—The dibromide was prepared in 87% yield from the above methyl ester and crystallised from carbon tetrachloride in pale yellow needles, m. p. 118° (Found: C, 39·4; H, 3·2; Br, 37·8. Calc. for $C_{14}H_{14}O_5Br_2$: C, 39·8; H, 3·3; Br, 37·9%).

Methyl 6-p-Methoxyphenyl-4-pyrone-2-carboxylate.—This *pyrone* was prepared in 70% yield by heating the foregoing dibromide with potassium acetate and calcium carbonate in methanol for 4 hr. It crystallised from water in needles, m. p. 131—133° (Found: C, 64·5; H, 4·5. $C_{14}H_{12}O_5$ requires C, 64·6; H, 4·65%). Its *picrate* crystallised from ethanol in yellow needles, m. p. 110° (Found: N, 8·7. $C_{20}H_{15}O_{12}N_3$ requires N, 8·6%). The pyrone was degraded with 20% aqueous potassium hydroxide to acetone, 4-methoxyacetophenone, and *p*-anisic, oxalic, and acetic acid.

Ethyl 5-4′-Methoxystyryl-1-phenylpyrazole-3-carboxylate.—This *ester* crystallised from ethanol in needles, m. p. 100° (Found: C, 72·4; H, 5·8; N, 8·15. $C_{21}H_{20}O_2N_2$ requires C, 72·4; H, 5·8; N, 8·0%). Its *picrate* crystallised from ethanol in yellow needles, m. p. 88° (Found: N, 12·0. $C_{27}H_{23}O_{10}N_5$ requires N, 12·1%). It yielded on ozonolysis *p*-anisaldehyde, the pyrazole aldehyde (VIII), and the mono-ester (IX).

Methods analogous to those above gave the following compounds:

Ethyl 5-4′-methoxystyryl-*iso*oxazole-3-carboxylate, needles (from ethanol), m. p. 77°. The *methyl* analogue crystallised from methanol in plates, m. p. 137° (Found: C, 65·1; H, 4·9; N, 5·7. $C_{14}H_{13}O_4N$ requires C, 64·8; H, 5·05; N, 5·4%).

Ethyl 6-o-methoxyphenyl-2 : 4-dioxo-5-hexenoate (90% from 2-methoxystyryl methyl ketone [15]), orange needles (from methanol), m. p. 80° (Found: C, 65·0; H, 5·9; OEt, 15·9. $C_{15}H_{16}O_5$

[11] Shoesmith and Connor, *J.*, 1927, 2231.

requires C, 65·2; H, 5·8; OEt, 16·3%); it gave a reddish-brown colour with ferric chloride, and a reddish-brown colour which changed into brown ⟶ bluish ⟶ colourless with titanium trichloride. The *methyl ester*, prepared by methanolysis, crystallised from methanol in orange needles, m. p. 97° (Found: C, 64·0; H, 5·3; OMe, 24·0. $C_{15}H_{14}O_5$ requires C, 64·1; H, 5·4; 2OMe, 23·7%).

Methyl 5 : 6-*dibromo*-6-o-*methoxyphenyl*-2 : 4-*dioxohexanoate* (84%), yellowish-white plates (from carbon tetrachloride), m. p. 133° (Found: C, 39·4; H, 3·3; Br, 38·0. $C_{14}H_{14}O_5Br_2$ requires C, 39·8; H, 3·3; Br, 37·9%).

Methyl 6-o-*methoxyphenyl*-4-*pyrone*-2-*carboxylate* (81%), needles (from water), m. p. 148° (Found: C, 64·5; H, 4·5. $C_{14}H_{12}O_5$ requires C, 64·6; H, 4·65%).

Ethyl 5-2′-*methoxystyryl*-1-*phenylpyrazole*-3-*carboxylate*, prisms (from methanol), m. p. 80° (Found: C, 72·6; H, 5·6; N, 8·2. $C_{21}H_{20}O_3N_2$ requires C, 72·4; H, 5·8; N, 8·0%): *picrate*, yellow needles (from methanol), m. p. 85° (Found: N, 12·1. $C_{27}H_{23}O_{10}N_5$ requires N, 12·1%). It gave on ozonolysis *o*-anisaldehyde, the aldehyde (VIII), and the mono-ester (IX).

Ethyl 5-2′-*methoxystyryl*)*isooxazole*-3-*carboxylate* (recovered from the reaction mixture by dilution and extraction with ether), prisms (from light petroleum), m. p. 56° (Found: C, 65·8; H, 5·4; N, 5·05. $C_{15}H_{15}O_4N$ requires C, 65·9; H, 5·5; N, 5·1%).

Ethyl 6-(3 : 4-*dimethoxyphenyl*)-2 : 4-*dioxohex*-5-*enoate* (98%), orange needles (from ethanol), m. p. 99° (Found: C, 62·4; H, 5·9; OEt, 14·1. $C_{16}H_{18}O_6$ requires C, 62·7; H, 5·9; OEt, 14·7%). It gave a brown colour with ferric chloride, a violet colour with sulphuric acid, and a reddish-brown colour which changed into brown ⟶ colourless with titanium trichloride.

Ethyl 5 : 6-*dibromo*-6-(3 : 4-*dimethoxyphenyl*)-2 : 4-*dioxohexanoate*, prisms, m. p. 134° (from carbon tetrachloride) (Found: Br, 35·3. $C_{16}H_{16}O_6Br_2$ requires Br, 34·3%), was dehydrobrominated to *ethyl* 6-(3 : 4-*dimethoxyphenyl*)-4-*pyrone*-2-*carboxylate* in absolute ethanol (yield, 72%), prisms (from ethanol), m. p. 175° (Found: C, 63·0; H, 5·3. $C_{16}H_{16}O_6$ requires C, 63·1; H, 5·3%).

Ethyl 5-(3 : 4-*dimethoxystyryl*)-1-*phenylpyrazole*-3-*carboxylate*, long needles (from ethanol), m. p. 113° (Found: C, 69·7; H, 5·9; N, 7·4. $C_{22}H_{22}O_4N_2$ requires C, 69·81; H, 5·9; N, 7·4%). It gave on ozonolysis the mono-ester (IX).

Ethyl 6-(3 : 4-*methylenedioxyphenyl*)-2 : 4-*dioxohex*-5-*enoate*, orange prisms (from acetone), m. p. 130° (Found: C, 62·05; H, 4·9; OEt, 15·8. $C_{15}H_{14}O_6$ requires C, 62·05; H, 4·9; OEt, 15·5%). It gave a brown colour with ferric chloride, a violet colour with sulphuric acid, and a reddish-brown colour which changed into brown ⟶ colourless with titanium trichloride.

Ethyl 5 : 6-*dibromo*-6-(3 : 4-*methylenedioxyphenyl*)-2 : 4-*dioxohexanoate*, prisms (from carbon tetrachloride), m. p. 117° (Found: C, 40·0; H, 3·05; Br, 35·6. $C_{15}H_{14}O_6Br_2$ requires C, 40·0; H, 3·1; Br, 35·5%).

Ethyl 6-(3 : 4-*methylenedioxyphenyl*)-4-*pyrone*-2-*carboxylate* (81%), yellowish-white needles (from benzene–light petroleum), m. p. 161° (Found: C, 62·2; H, 4·1. $C_{15}H_{12}O_6$ requires C, 62·5; H, 4·2%).

Ethyl 5-(3 : 4-*methylenedioxystyryl*)-1-*phenylpyrazole*-3-*carboxylate*, long needles (from ethanol), m. p. 191° (Found: C, 69·2; H, 4·9; N, 7·8. $C_{21}H_{18}O_4N_2$ requires C, 69·6; H, 5·0; N, 7·7%).

Ethyl 5-(3 : 4-*methylenedioxystyryl*)*isooxazole*-3-*carboxylate*, needles (from ethanol), m. p. 122° (Found: C, 63·0; H, 4·7; N, 5·2. $C_{15}H_{13}O_5N$ requires C, 62·7; H, 4·6; N, 4·9%).

Ethyl 6-2′-*furyl*-2 : 4-*dioxohex*-5-*enoate*, yellow needles [from light petroleum (b. p. 60—80°)], m. p. 80° (Found: C, 60·8; H, 5·0; OEt, 18·9. $C_{12}H_{12}O_5$ requires C, 61·0; H, 5·1; OEt, 19·1%). The *methyl ester*, obtained by methanolysis, crystallised from methanol in needles, m. p. 100° (Found: C, 59·7; H, 4·6; OMe, 13·6. $C_{11}H_{10}O_5$ requires C, 59·5; H, 4·5; OMe, 14·0%). Both esters gave a dark-brown colour with ferric chloride, a dark red colour with sulphuric acid, and a reddish-brown colour which changed into bluish ⟶ violet ⟶ colourless with titanium trichloride.

Ethyl 6-2′-*furyl*-4-*pyrone*-2-*carboxylate*.—The purified dibromide (5 g.), m. p. 101°, prepared from the foregoing ester was dehydrobrominated for 2 hr. The ethanolic filtrate was concentrated, diluted with water, and extracted with ether, and the residue (2·6 g.) recovered was extracted with light petroleum. The latter extract yielded the *pyrone* (1 g.) which crystallised from light petroleum in needles, m. p. 103° (Found: C, 60·9; H, 4·4. $C_{12}H_{10}O_5$ requires C, 61·5; H, 4·3%).

Ethyl 5-(2-2′-*furylvinyl*)*pyrazole*-3-*carboxylate* crystallised from ethanol in needles, m. p. 116° (Found: C, 70·5; H, 5·3; N, 9·2. $C_{14}H_{14}O_3N_2$ requires C, 70·1; H, 5·3; N, 9·1%).

Ethyl 5-(2-2′-*furylvinyl*)*isooxazole*-3-*carboxylate* crystallised from ethanol in needles, m. p. 104° (Found: C, 61·8; H, 4·7; N, 6·3. $C_{12}H_{11}O_4N$ requires 61·8; H, 4·8; N, 6·0%).

Ethyl 6-p-*Dimethylaminophenyl-2 : 4-dioxohex-5-enoate.*—This was prepared by condensation of *p*-dimethylaminostyryl methyl ketone [16] (10 g., 1 mol.) with ethyl oxalate (8·1 g., 1 mol.). The sodium salt was acidified with acetic acid, a deep-red solid (15 g.), m. p. 115°, separating. When refluxed with light petroleum, the ester was extracted, leaving an insoluble brown dye (5 g.), m. p. 190°. The *ester* crystallised from light petroleum in red plates, m. p. 122° (Found: C, 66·5; H, 6·6; N, 4·6. $C_{16}H_{19}O_4N$ requires C, 66·4; H, 6·6; N, 4·8%). It gave a reddish-brown colour with ferric chloride, and a deep-red colour which changed into brown ⟶ black ⟶ colourless with titanium trichloride. Its solution in hydrochloric acid is only pale-yellow. The dye crystallised from benzene in brown aggregate needles, m. p. 190° (Found: C, 71·9; H, 7·4; N, 8·5%).

Ethyl 5-p-*dimethylaminostyryl-1-phenylpyrazole-3-carboxylate* crystallised from ethanol in prisms, m. p. 114° (Found: C, 72·6; H, 6·4; N, 11·6. $C_{22}H_{22}O_2N_2$ requires C, 73·1; H, 6·4; N, 11·6%). It gave on ozonolysis the monoester (IX).

Ethyl 5-p-*dimethylaminostyrylisooxazole-3-carboxylate* crystallised from ethanol in prisms, m. p. 123° (Found: C, 66·8; H, 6·3; N, 10·0. $C_{16}H_{16}O_3N_2$ requires C, 67·1; H, 6·3; N, 9·8%).

CHEMISTRY DEPARTMENT, FACULTY OF SCIENCE,
ALEXANDRIA UNIVERSITY, MOHARRAM BEY, ALEXANDRIA. [*Received, April 13th*, 1956.]

[16] Sachs and Lewin, *Ber.*, 1902, **35**, 3569.

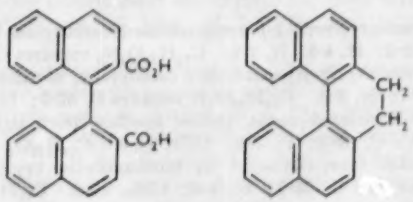
---

706. *Diaryl-2 : 2′-disulphonic Acids and Related Compounds. Part II.* The Optical Stability of a Cyclic 2 : 2′-Thiolsulphonate.*

By W. L. F. ARMAREGO and E. E. TURNER.

The distrychnine salt of 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonic acid has been resolved. The disodium salt, the disulphonyl chloride, and the dianilide have high optical stability. The cyclic 2 : 2′-thiolsulphonate has a half-life of 24 minutes in boiling ethylbenzene and one of about 5 hours in boiling toluene. It is thus more stable than 9 : 10-dihydro-3 : 4-5 : 6-dibenzophenanthrene.

1 : 1′-DINAPHTHYL-2 : 2′-DICARBOXYLIC ACID (I) possesses very high optical stability. Yet active 9 : 10-dihydro-3 : 4-5 : 6-dibenzophenanthrene (II), in which the energy of approach of two carbon atoms has been overcome, has the smaller, but still very considerable, optical stability which is represented by the statement that it has a half-life of



(I) (II)

13 minutes in boiling ethylbenzene and about 3 hours in boiling toluene.[1] It seems probable therefore that since the active forms of diphenyl-2 : 2′-disulphonic acid (III; R = H) undergo complete racemisation in a few minutes in boiling aqueous solution,[2] derived cyclic types such as the 2 : 2′-thiolsulphonate (IV; R = H) or the 2 : 2′-disulphide (V; R = H) would have low configurational stability.

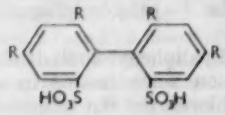
It appeared to us that the optical stability relationship between types (III) and (IV), or (III) and (V), could well be studied by using a disulphonic acid of high optical stability, and 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonic acid (III; R = Me) has been

* Part I, *J.*, 1956, 1665.

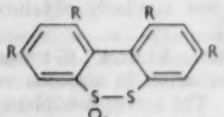
[1] Hall and Turner, *J.*, 1955, 1242; Hall, following note.

[2] Lesslie and Turner, *J.*, 1932, 2394.

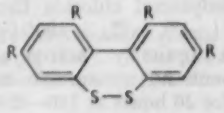
selected for examination. It was synthesised from 2 : 4-xylidine ($NH_2 = 1$). This was sulphonated,[3] and the amino-group replaced by either bromine [3] or iodine. The derived sulphonyl chlorides were converted into phenyl 2-bromo(or 2-iodo)-3 : 5-dimethylbenzenesulphonate, which was heated with copper. The route through the iodo-compounds was the better. The phenyl 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonate so formed



(III)



(IV)



(V)

was, as expected, difficult to hydrolyse, but by using four molecular proportions of sodium *n*-butoxide in boiling butanol an 89% conversion into the sodium disulphonate was achieved. The alkali salts of 2-iodo-3 : 5-dimethylbenzenesulphonic acid gave very poor yields of the tetramethyldiphenyldisulphonates when their aqueous solutions were boiled in presence of copper powder and copper sulphate (see Part I).

4 : 6 : 4′ : 6′-Tetramethyldiphenyl-2 : 2′-disulphonyl chloride, obtained from the disodium salt and phosphorus pentachloride, could not be reduced to the 2 : 2′-dithiol. Use of an excess of zinc and hydrochloric acid, or hydriodic acid, gave polymeric material. It was therefore impossible to obtain the cyclic 2 : 2′-disulphide (V; R = Me) by the standard method of oxidising the dithiol. Reduction of the disulphonyl chloride with hot aqueous alkaline alkali sulphite gave the sodium disulphinate: on further heating after addition of excess of mineral acid, the precipitated unstable disulphinic acid passed into the thiolsulphonate (IV; R = Me). This compound was less conveniently obtained by the restricted reduction of the disulphonyl chloride with zinc and acid. By reduction of the thiolsulphonate with hydriodic–acetic acid the 2 : 2′-dithiol was produced in low yield, but attempted purification led to polymerised material. Reduction of the thiolsulphonate with lithium aluminium hydride in ether gave the 2′-mercapto-2-sulphinic acid, from which, by methylation, 4 : 6 : 4′ : 6′-tetramethyl-2-methylsulphonyl-2′-methylthiodiphenyl was formed.

It can be seen from a model that if the two sulphur atoms in the unsubstituted thiolsulphonate (IV; R = H) have approximately the same radius (1·0 Å) that they would have in the cyclic disulphide (V; R = H), a strainless form is obtained when the angle of twist between the (collinear) benzene nuclei is about 35° and the sulphur angle is about 90°. Into such a molecule two methyl groups can be put into the 6- and 6′-positions only with some strain.

Treating an aqueous solution of one mol. of sodium 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonate with an aqueous solution of two mols. of strychnine hydrochloride gave the almost pure (−)-base (−)-acid salt, and by evaporation of the mother-liquor crude (−)-base (+)-acid salt was obtained, initially as an oil. The less soluble salt became optically pure after one crystallisation from methanol and had $[\alpha]_{5461}^{19\cdot2}$ −100·0° (±0·5°), $[\alpha]_{5791}^{19\cdot2}$ −96·0° (±0·5°) (in $CHCl_3$).

Treatment with sodium hydroxide gave the sodium (−)-disulphonate, which after crystallisation from ethanol had $[\alpha]_{5461}^{20}$ −39·0° (±0·5°), $[\alpha]_{5791}^{20}$ −35·0° (±0·5°) (in H_2O). Crystallisation from ethanol of the sodium disulphonate obtained from the more soluble strychnine salt gave the sodium (+)-disulphonate with $[\alpha]_{5461}^{20}$ +40·5° (±0·5°), $[\alpha]_{5791}^{20}$ +35·0° (±0·5°) (in H_2O). The sign of rotation of the sodium salts was reversed in ethanol: the values of the rotation for various ethanol–water mixtures are given in the Experimental section.

By the action of phosphorus pentachloride on the (−)-sodium salt, 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonyl chloride was obtained with $[\alpha]_{5461}^{20}$ −94·5° (±0·5°), $[\alpha]_{5791}^{20}$ −83·5° (±0·5°) (in $CHCl_3$): the (+)-disulphonyl chloride, from the (+)-sodium

[3] Junghahn, *Ber.*, 1912, **35**, 3747.

salt, had $[\alpha]^{20}_{5461}$ +95·0° (±0·5°), $[\alpha]^{20}_{6791}$ +83·5° (±0·5°) (in $CHCl_3$). The (−)- and the (+)-disulphonyl chloride gave, respectively, a (+)-, $[\alpha]^{22}_{5461}$ +238° (±1°), and a (−)-disulphonanilide, $[\alpha]^{22}_{5461}$ −237° (±1°). The (−)-disulphonyl chloride was heated with aqueous alkaline sodium sulphite until it had all dissolved, excess of dilute mineral acid was added and the mixture heated. The cyclic thiolsulphonate so obtained was strongly dextrorotatory, with $[\alpha]^{20}_{5461}$ +253° (±1°) and $[\alpha]^{20}_{6791}$ +188° (±1°) (in $CHCl_3$). From the (+)-disulphonyl chloride there was similarly obtained the (−)-thiolsulphonate, $[\alpha]^{20}_{5461}$ −252° (±1°), $[\alpha]^{20}_{6791}$ −190° (±1°).

The optically active sodium 4 : 6 : 4' : 6'-tetramethyldiphenyl-2 : 2'-disulphonate underwent no measurable racemisation in aqueous solution when heated in a closed vessel for 26 hours at 180—200°. The active disulphonyl chloride did not racemise during half an hour at 170—175° in a vacuum. The active disulphonanilides remained unchanged when their solutions in *m*-nitrotoluene were boiled for 1½ hours. The (−)-thiolsulphonate had a half-life of 24 minutes in boiling ethylbenzene solution, that is about twice the half-life (13 min.) of 9 : 10-dihydro-3 : 4-5 : 6-dibenzophenanthrene in the same solvent at the same temperature. The half-life of the (+)-thiolsulphonate in boiling toluene was 291 (±2) min. The activation energy calculated from the two rate determinations is 31 kcal./mole.

Experimental

Polarimetric readings were made with $l = 2$. The chloroform used was of B.P. grade.

Phenyl 2-Bromo-3 : 5-dimethylbenzenesulphonate.—2 : 4-Xylidine was sulphonated with some modification of the procedure described by Junghahn.[8] By recovering and sulphonating unchanged base, a 68% yield was obtained. The solid diazo-sulphonate was heated at 70° with 48% hydrobromic acid, and the sodium sulphonate was salted out with sodium chloride. After treatment of the dehydrated sodium salt with phosphorus pentachloride, the bulk of the phosphoryl chloride was removed by distillation before the addition of ice-water. The sulphonyl chloride was filtered off and dried in a vacuum.

The sulphonyl chloride (56 g., 1 mol.) was dissolved in dry pyridine (100 c.c.), and phenol (40 g., 2 mol.) added. The dark reddish solution was heated at 100° for ½ hr., then cooled and poured into ice-water. The pale yellow oil that separated was washed with dilute hydrochloric acid and with dilute alkali. The solid *ester* obtained crystallised from ethanol as flat prisms, m. p. 96—97° (48 g., 71%) (Found: Br, 23·1. $C_{14}H_{13}O_3BrS$ requires Br, 23·4%).

An alternative procedure, which gave a purer crude product, was to heat the sulphonyl chloride (1 mol.) with phenol (2 mol.) and anhydrous sodium carbonate (1·5 mol.) for 1·5 hr. at 100°.

2 : 4-Dinitrophenyl 4-Bromo-3 : 5-dimethylbenzenesulphonate.—To a solution of 2 : 4-dinitrophenol (2·3 g.) in chloroform (35 c.c.) was added a solution of the above sulphonyl chloride (7 g.) in dry pyridine (2·2 c.c.). The mixture was boiled under reflux for 2 hr. The chloroform was distilled off and the residue treated with cold water. The *ester* crystallised from a large bulk of methanol or ethanol in long yellow needles, m. p. 147—148° (19%) (Found: N, 6·55. $C_{14}H_{11}O_7N_2Br$ requires N, 6·5%).

Phenyl 4 : 4' : 6 : 6'-Tetramethyldiphenyl-2 : 2'-disulphonate.—Method A. Phenyl 2-bromo-3 : 5-dimethylbenzenesulphonate (30 g.) was heated at 240—260°, and copper bronze (60 g.) added at such a rate that the temperature of the mixture did not rise above 280°. When the reaction was complete, the somewhat cooled mixture was treated with chlorobenzene and filtered, and the copper washed with chlorobenzene. The solvent was distilled off and the residual *disulphonate* was crystallised from butan-1-ol or glacial acetic acid, forming flat rhombs, m. p. 180—181° (39%; overall yield on xylidinesulphonic acid 12%) (Found: C, 63·7; H, 5·0; S, 12·3%; *M*, ebullioscopic in benzene, 536. $C_{28}H_{34}O_6S_2$ requires C, 64·3; H, 5·0; S, 12·4%; *M*, 523).

2-Iodo-3 : 5-dimethylbenzenesulphonyl Chloride.—The above diazo-sulphonate (160 g., 1 mol.) was added to a solution of potassium iodide (160 g., 1½ mol.) in 25% v/v sulphuric acid (800 c.c.) and heated on a boiling-water bath until evolution of nitrogen ceased. On cooling, the sulphonic acid separated as plates, and more was obtained by vacuum-evaporation of the mother-liquor. The acid was dried in a vacuum over H_2SO_4. It lost iodine when exposed to light. The yield was 231 g.

The acid (156 g.) was gradually treated with phosphorus pentachloride (156 g.) with ice-water cooling. After 1 hr., most of the phosphoryl chloride was distilled off under vacuum and the residue treated with ice-cold water. The dried *sulphonyl chloride* crystallised from light petroleum (b. p. 60—80°) in prisms, m. p. 86—87° (66%) (5·245 mg. gave 5·820 mg. of AgI + AgCl. $C_8H_8O_2ClIS$ requires 5·991 mg.).

The *sulphonamide*, resulting from the interaction of the chloride and concentrated aqueous ammonia, crystallised in needles from dilute ethanol (Found: I, 40·2; N, 4·2. $C_8H_{10}O_2INS$ requires I, 40·8; N, 4·5%).

Phenyl 2-Iodo-3 : 5-dimethylbenzenesulphonate.—The iodo-sulphonyl chloride (265 g., 1 mol.) was heated at 100° with phenol (2 mol.) and sodium carbonate (1½ mol.). After the standard procedure, the *ester* crystallised from ethanol as plates, m. p. 105—106° (94%) (Found: C, 43·2; H, 3·5. $C_{14}H_{13}O_3IS$ requires C, 43·3; H, 3·4%).

Phenyl 4 : 6 : 4′ : 6′-Tetramethyldiphenyl-2 : 2′-disulphonate.—Method B. The iodo-ester (129 g.) was heated at 170—180° with copper bronze (100 g.). The yield of disulphonate was 70 g. (80%) (the overall yield calculated on xylidinesulphonic acid was 41·5%).

Di-(2-iodo-3 : 5-dimethylphenyl) Disulphide.—A solution of the iodo-sulphonyl chloride (5·9 g.) in boiling glacial acetic acid (60 c.c.) was treated with 55% (w/w) hydriodic acid (50 c.c.). After an hour at room temperature the mixture was poured into a saturated aqueous solution of sodium hydrogen sulphite. The solid *disulphide* was collected, washed, dried, and crystallised from glacial acetic acid; it formed long pale yellow needles, m. p. 160—161° (4·0 g., 85%) (Found: I, 48·4. $C_{16}H_{16}I_2S_2$ requires I, 48·2%). At 190—220° the disulphide reacted with copper bronze with uncontrollable vigour, and no tetramethylthianthren could be isolated.

Sodium and Barium Salts of 4 : 6 : 4′ : 6′-Tetramethyldiphenyl-2 : 2′-disulphonic Acid.—Sodium (3 g., 4 atom-equivs.) was dissolved in butan-1-ol (100 c.c.), and the solution added to one of phenyl 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonate (16·7 g., 1 mol.) in butan-1-ol (160 c.c.). The mixture was boiled under reflux for 3 hr., and then distilled until the residual volume was about 75 c.c. The liquid was poured into water (200 c.c.), and the solution boiled, filtered, and acidified with 2N-hydrochloric acid. Phenol was removed by extraction with ether, and the aqueous solution, after being neutralised (to Congo-red) with 10% aqueous sodium hydroxide, was filtered and concentrated to about 50 c.c. On cooling, the *sodium salt* crystallised in platelets (88% yield of anhydrous salt, after drying at 120°) (Found: S, 15·8. $C_{16}H_{16}O_6S_2Na_2$ requires S, 15·5%). The salt was hygroscopic and was soluble in ethanol. When only 2 mol. of sodium butoxide were used, 30% of unchanged ester was recovered after 12 hours' boiling.

The barium salt separated in fine needles when a 5% solution of barium chloride was added to a warm aqueous solution of the sodium disulphonate. The *barium salt* was very sparingly soluble in water and did not react under normal conditions with phosphorus pentachloride (Found: Ba, 24·7, 24·5. $C_{16}H_{16}O_6S_2Ba,3H_2O$ requires Ba, 24·6%).

4 : 6 : 4′ : 6′-Tetramethyldiphenyl-2 : 2′-disulphonyl Chloride.—A mixture of the sodium disulphonate (anhydrous; 31·0 g., 1 mol.) with phosphorus pentachloride (32·0 g., 2 mol.) was heated at 100° for 10 min. The cooled liquid was poured into water and the resulting yellow solid *dichloride* was washed and dried and crystallised from glacial acetic acid, forming needles, m. p. 164° (23 g., 77%) (Found: C, 47·0; H, 4·1; S, 15·9. $C_{16}H_{16}O_4Cl_2S_2$ requires C, 47·2; H, 3·9; S, 15·7%). With phenol in dry pyridine it gave the diphenyl disulphonic ester, m. p. 181°, in 31% yield and with aniline it gave *4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonanilide* (37%), cubic crystals, m. p. 208—209° (from ethanol) (Found: N, 5·7. $C_{28}H_{28}O_4N_2S_2$ requires N, 5·4%).

Reduction of 4 : 6 : 4′ : 6′-Tetramethyldiphenyl-2 : 2′-disulphonyl Chloride.—(a) *With alkaline sodium sulphite.* The disulphonyl chloride (7·8 g.) was shaken at 100° with 30% sodium sulphite solution (250 c.c.) and 10% sodium hydroxide solution (20 c.c.). With intermittent shaking, the suspended chloride dissolved in 8—10 hr. The yellow solution was acidified with excess of 2N-sulphuric acid and heated on a boiling-water bath until all the material that separated had coagulated. The cyclic *thiolsulphonate* (*1 : 3 : 8 : 10-tetramethyldibenzo*[ce]*dithiin 5 : 5-dioxide*; Ring Index no. 1936) was collected, dried, and crystallised from glacial acetic acid (prisms, m. p. 177—178°) or from butan-1-ol (needles, m. p. 177—178°) (yield, 4·2 g.) (Found: C, 62·9; H, 4·9; S, 21·4%; *M*, ebullioscopic in benzene, 316. $C_{16}H_{16}O_2S_2$ requires C, 63·1; H, 5·2; S, 21·0%; *M*, 304).

(b) *With zinc dust and hydrochloric acid.* The disulphonyl chloride (4 g., 1 mol.) was dissolved in hot absolute ethanol (50 c.c.), zinc dust (5 g., 8 atom-equivs.) added, and the mixture cooled to 10°. Concentrated hydrochloric acid (20 c.c.) was added at such a rate that the temperature

did not rise above 20°. The mixture was heated at 100° for 10 min., filtered, and poured into water (200 c.c.). The solid separating crystallised from glacial acetic acid as prisms (2·0 g.), m. p. 177° undepressed by admixture with the thiolsulphonate from (a).

When reduction was attempted with a large excess of zinc dust and hydrochloric acid, a white polymeric substance was obtained.

(c) *With hydriodic–acetic acid.* A solution of the disulphonyl chloride (2 g.) in boiling glacial acetic acid (30 c.c.) was treated with hydriodic acid (*d* 1·7) (20 c.c.) and glacial acetic acid (20 c.c.). The mixture was boiled and then left to cool for 24 hr. The product resembled that obtained by using excess of zinc and hydrochloric acid.

Reduction of the Thiolsulphonate.—(*a*) The thiolsulphonate (0·5 g.) was dissolved in boiling glacial acetic acid (10 c.c.), and 55% w/w hydriodic acid (10 c.c.) added. After 5 min. the mixture was cooled and 4:6:4′:6′-*tetramethyldiphenyl*-2:2′-*dithiol* crystallised. It separated from glacial acetic acid in rectangular plates, m. p. 138—139° (Found: C, 71·2; H, 6·7; S, 22·1. $C_{16}H_{18}S_2$ requires C, 70·0; H, 6·6; S, 23·4%). It was soluble in alkali but readily oxidised in air to an alkali-insoluble product.

(*b*) Reduction with lithium aluminium hydride in ethereal solution gave 2′-*mercapto*-4:6:4′:6′-*tetramethyldiphenyl*-2-*sulphinic acid* (Found: C, 63·7; H, 6·1; S, 20·4. $C_{16}H_{18}O_2S_2$ requires C, 63·1, H, 5·9; S, 20·9%). Methylation of this substance with methyl sulphate in alkaline solution gave *methyl* 4:6:4′:6′-*tetramethyl*-2′-*methylthio*-2-*diphenylyl sulphone*, plates, m. p. 146—147 (from butan-1-ol) (Found: C, 65·0; H, 6·7. $C_{18}H_{22}O_2S_2$ requires C, 64·7; H, 6·6%).

Optical Resolution of Strychnine 4:6:4′:6′-*Tetramethyldiphenyl*-2:2′-*disulphonate.*—Strychnine (66·88 g., 2 mol.) was dissolved in water (2 l.) containing concentrated hydrochloric acid (7·3 g., 2 mol.) by boiling. Anhydrous sodium 4:6:4′:6′-tetramethyldiphenyl-2:2′-disulphonate (41·4 g., 1 mol.), dissolved in water (400 c.c.), was added to the hot solution. A precipitate suddenly separated. The mixture was kept overnight and then filtered. The solid was dried in a vacuum at 67° and crystallised from methanol (10 l.) as rhombs (25 g.), m. p. 340° (decomp.), $[\alpha]^{19\cdot2}_{5461}$ −100·0° (±0·5°), $[\alpha]^{19\cdot2}_{5791}$ −96·0° (±0·5°) (*c* 1·0310 in $CHCl_3$). Recrystallisation of this (−)-*base* (−)-*acid salt* from a large volume of methanol did not affect the specific rotation (Found: C, 65·2; H, 6·3. $C_{58}H_{62}O_{10}N_4S_2,2CH_3{\cdot}OH$ requires C, 65·3; H, 6·4%).

The first aqueous filtrate was concentrated to 400 c.c. An oil separated. This was isolated by decanting off the mother-liquor and washing the residue twice with a little water. The washings were added to the mother-liquor, and the solution was concentrated to 200 c.c. More oil separated. The combined oils, after being washed, were then dried in a vacuum. The almost pure solid (−)-*base* (+)-*acid salt* so obtained was very soluble in water and in cold methanol {yield 25 g.; m. p. 270° (decomp.; softening at 250°), $[\alpha]^{19\cdot8}_{5461}$ −70·5° (±0·5°), $[\alpha]^{19\cdot8}_{5791}$ −61·0° (±0·5°) (*c* 1·0905 in $CHCl_3$)} (Found: C, 61·2; H, 6·4. $C_{58}H_{62}O_{10}N_4S_2,6H_2O$ requires C, 61·2; H, 6·2%).

Sodium (−)-4:6:4′:6′-*Tetramethyldiphenyl*-2:2′-*disulphonate.*—A chloroform solution of the (−)-base (−)-acid salt (22 g.) was thrice extracted with 10% aqueous sodium hydroxide (in all about 400 c.c.). The combined alkaline solutions were extracted with chloroform until the latter had no optical activity. The alkaline solution was neutralised with concentrated hydrochloric acid and evaporated in a vacuum on a water-bath. The residual solid was dried at 120—130° for 2 hr. and then extracted with hot absolute ethanol until the extract ceased to possess optical activity. The ethanol solution (about 1 l.) was filtered and concentrated to about 150 c.c. On cooling, the disodium (−)-salt separated as needles (8·5 g.). After being dried in a vacuum it had $[\alpha]^{18}_{5461}$ −39·0° (±0·5°), $[\alpha]^{20}_{5791}$ −35·0° (±0·5°) (*c* 1·1015 in H_2O), and $[\alpha]^{18}_{5461}$ +9·5° (±0·5°), $[\alpha]^{20}_{5791}$ +8·0° (±0·5°) (*c* 0·968 in absolute EtOH). Evaporation of the ethanolic mother-liquor gave 3·0 g. of almost pure (−)-salt.

Sodium (+)-4:6:4′:6′-*Tetramethyldiphenyl*-2:2′-*disulphonate.*—From the (−)-base (+)-acid salt (22 g.), sodium (+)-salt was obtained, having $[\alpha]^{20}_{5461}$ +40·5° (±0·5°), $[\alpha]^{20}_{5791}$ +35·0° (±0·5°) (*c* 1·0870 in H_2O), and $[\alpha]^{18}_{5461}$ −9·5° (±0·5°), $[\alpha]^{18}_{5791}$ −9·0° (±0·5°) (*c* 0·9680 in EtOH).

Rotations in aqueous ethanol are tabulated.

A solution of the sodium salt in water, with α_{5461} +0·56° and α_{5791} +0·49° (*l* = 2), was heated for 26 hr. in a sealed tube at 180—200° and although the resulting solution was slightly turbid the rotation was unchanged.

Active 4:6:4′:6′-*Tetramethyldiphenyl*-2:2′-*disulphonyl Chlorides.*—Anhydrous sodium (−)-tetramethyldiphenyldisulphonate (6 g.) was treated with an equal weight of phosphorus

Effect of adding water to absolute ethanol solutions (20 *ml.*; *c* 0·968; *l* = 2) *of sodium* 4 : 6 : 4′ : 6′-*tetramethyldiphenyl*-2 : 2′-*disulphonates.*

Added water (ml.)	(−)-Salt		(+)-Salt		Added water (ml.)	(−)-Salt		(+)-Salt	
	α^{20}_{5461}	α^{20}_{5791}	α^{18}_{5461}	α^{18}_{5791}		α^{20}_{5461}	α^{20}_{5791}	α^{18}_{5461}	α^{18}_{5791}
0·0	+0·18°	+0·15°	−0·19°	−0·17°	2·5	−0·41°	−0·39°	+0·40°	+0·35°
0·1	+0·13	+0·10	−0·12	−0·12	3·0	−0·42	−0·40	+0·41	+0·36
0·3	+0·02	0·00	—	—	3·5	−0·43	−0·41	—	—
0·5	−0·07	−0·06	0·00	+0·01	4·0	−0·44	−0·41	+0·43	+0·39
0·7	−0·13	−0·13	+0·09	+0·06	5·0	−0·42	−0·39	+0·40	+0·35
1·0	−0·22	−0·21	+0·19	+0·15	7·0	−0·39	−0·37	+0·37	+0·32
1·5	−0·32	−0·31	+0·30	+0·25	9·0	−0·36	−0·34	+0·34	+0·31
2·0	−0·39	−0·37	+0·36	+0·31	11·0	−0·32	−0·31	+0·32	+0·29

Error ± 0·01°.

pentachloride, the procedure being as for the (±)-material. The (−)-*chloride* crystallised from glacial acetic acid in yellow needles (2·7 g.), m. p. 165°, $[\alpha]^{20}_{5461}$ −94·5° (±0·5°), $[\alpha]^{20}_{5791}$ −83·5° (±0·5°) (*c* 1·0300 in $CHCl_3$) (Found: C, 46·7; H, 4·1%).

The (+)-*chloride*, obtained from the sodium (+)-sulphonate and phosphorus pentachloride, had m. p. 165°, $[\alpha]^{20}_{5461}$ +95·0° (±0·5°), $[\alpha]^{20}_{5791}$ +83·5° (±0·5°) (*c* 1·0415 in $CHCl_3$) (Found: C, 47·5; H, 4·2%).

4 : 6 : 4′ : 6′-*Tetramethyldiphenyl*-2 : 2′-*disulphonanilides*.—(−)-4 : 6 : 4′ : 6′-Tetramethyldiphenyl-2 : 2′-disulphonyl chloride was heated in previously distilled aniline for ½ hr. at 100°. The mixture formed was poured into dilute hydrochloric acid, and the solid filtered, washed, and dried. The (+)-*anilide* crystallised from ethanol in prisms, m. p. 218—219°, $[\alpha]^{20}_{5461}$ +238° (±1°) (*c* 0·4220 in $CHCl_3$) (Found: N, 5·2%).

The (−)-*anilide* had m. p. 218—219°, $[\alpha]^{20}_{5461}$ −237·0° (±1°) (*c* 0·4250 in $CHCl_3$) (Found: N, 5·2%).

A solution of the (+)-dianilide in *m*-nitrotoluene with α_{5461} +0·43° and α_{5791} +0·35° was boiled under reflux for 2½ hr. The cooled solution had unchanged rotation.

4 : 6 : 4′ : 6′-*Tetramethyldiphenyl*-2 : 2′-*thiolsulphonate* (1 : 3 : 8 : 10-*Tetramethyldibenzo*[*ce*]-*dithiin* 5 : 5-*Dioxide*).—Finely powdered (−)-4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-disulphonyl chloride (1·8 g.) was shaken at the temperature of a boiling-water bath with 30% aqueous sodium sulphite solution (100 c.c.) and 10% aqueous sodium hydroxide (10 c.c.), dissolving completely in 3 hr. The solution was filtered, cooled, acidified with 50% sulphuric acid (about 100 c.c.), and heated on a boiling-water bath until all the oil that separated had solidified (about ½ hr.). The mixture was cooled and the solid filtered off, dried in a vacuum, and crystallised from butan-1-ol (about 10 c.c.). The (+)-*thiolsulphonate* so obtained, after being dried in a vacuum (0·7 g.), had m. p. 178—178·5°, $[\alpha]^{20}_{5461}$ +253·0° (±1°), $[\alpha]^{20}_{5791}$ +188·0° (±1°) (*c* 0·5705 in $CHCl_3$) (Found: C, 62·9; H, 5·6%).

The (−)-*thiolsulphonate* (0·7 g. from 1·7 g.) had m. p. 178—178·5°, $[\alpha]^{20}_{5461}$ −252°, $[\alpha]^{20}_{5791}$ −190° (±1°) (*c* 0·5385 in $CHCl_3$) (Found: C, 63·0; H, 5·3%).

The rate of racemisation in boiling ethylbenzene was measured for a solution (25 c.c.) containing 0·0833 g. of (−)-thiolsulphonate. The temperature was rapidly raised to the b. p. and after a suitable interval the solution was rapidly cooled to room temperature. Polarimetric readings were taken at 21° and the solution then rapidly heated to the b. p., and so on. α_{5461} (*l* = 2) fell from −1·49° to 0°, and α_{5491} from −1·12° to 0° in 143 min. From a logarithmic plot, *k* was found to be 2·8 (±0·2) × 10^{-3} $min.^{-1}$ and the half-life 24 ± 1 min.

The rate of racemisation in boiling toluene was measured for a solution (25 c.c.) containing 0·0878 g. of the (+)-thiolsulphonate. From a logarithmic plot, *k* was found to be 2·38 (±0·02) × 10^{-3} $min.^{-1}$ and the half-life 291 ± 2 min.

We thank Imperial Chemical Industries Limited for a grant, and Bedford College for a Post-Graduate Studentship (to W. L. F. A.).

Bedford College, University of London. [*Received, April 9th*, 1956.]

707. *The Racemisation of* 9 : 10-*Dihydro*-3 : 4-5 : 6-*dibenzophenanthrene.*

By D. Muriel Hall.

The rates of racemisation of this hydrocarbon were previously [1] determined in boiling ethylbenzene and in boiling toluene; from the values found ($k = 3{\cdot}18 \times 10^{-3}$ min.$^{-1}$ and $5{\cdot}3 \times 10^{-2}$ min.$^{-1}$, respectively) the activation energy was calculated as 34 kcal./mole. This appeared to be rather high and a reinvestigation has given the value of 31 kcal./mole.

The boiling point of toluene is particularly sensitive to small changes in pressure. The racemisation has now been repeated in toluene which had been carefully fractionated and had b. p. 110·5°/760·5 mm.; heating was restricted to times when the atmospheric pressure was 760 ± 3 mm. The value of k so obtained is $4{\cdot}4 \times 10^{-3}$ min.$^{-1}$; half-life, 158 min. The racemisation has also been carried out in boiling dioxan, b. p. 101·0°/762 mm., giving k, $1{\cdot}53 \times 10^{-3}$ min.$^{-1}$; half-life, 453 min.

These rates, together with that in ethylbenzene, give an activation energy of 31 kcal./mole. (The change of solvent is unlikely to have much effect on the rate of racemisation of such a hydrocarbon.) The activation energy for the racemisation of 9 : 10-dihydro-3 : 4-5 : 6-dibenzophenanthrene is thus the same as that for the racemisation of 4 : 6 : 4′ : 6′-tetramethyldiphenyl-2 : 2′-thiolsulphonate,[2] although the latter is about twice as stable optically.

Experimental.—Racemisations were carried out as previously described,[1] *viz.*, by heating the solution rapidly to the boiling point and, after a suitable interval, cooling it quickly in ice-water. Polarimetric readings were then made at room temperature, the solution returned to the flask, and re-heated for a further period. The main sources of error (apart from fluctuations in pressure) are thus uncertainties in the times and the small increases in concentration resulting from loss of solvent by evaporation.

Bedford College, University of London. [*Received, May 28th*, 1956.]

[1] Hall and Turner, *J.*, 1955, 1242.
[2] Armarego and Turner, preceding paper.

---

708. *The Mechanism of the Pinacol–Pinacone Rearrangement. Part III.*[1] *Evidence on General Acid Catalysis.*

By J. F. Duncan and K. R. Lynn.

It has previously been established that the pinacol–pinacone rearrangement in aqueous acid solution is strongly catalysed by the H_3O^+ ion, but the only other acidic species besides H_3O^+ which has been discussed is the bisulphate ion, which does not appear to catalyse the reaction.[1]

We have now studied the reaction in aqueous solutions of a number of weak acids, and it has been found that the reaction does not proceed at a measurable rate except by catalysis by the H_3O^+ ion.

Results.—Catalysing acids. The reaction rate was determined with oxalic acid and phosphoric acid. The results are given in the Table.

The hydrogen-ion concentrations in the various solutions are shown in the Table. These have been calculated by using a value of $5{\cdot}7 \times 10^{-2}$ for the acidity constant for oxalic acid [2] (value at 18°) and of $1{\cdot}59 \times 10^{-2}$ for phosphoric acid. The latter value (for 113·5°) was calculated from values at lower temperatures by using Everett and Wynne-Jones's technique,[3] but acidity constants are not available over a sufficiently wide temperature range to permit similar calculation for oxalic acid. With both acids the ionic strength was always less than

[1] Parts I and II, Duncan and Lynn, *J.*, 1956, 3512, 3519.
[2] Bell, "Acid–base Catalysis," Oxford Univ. Press, 1941; Parton and Nicholson, *Trans. Faraday Soc.*, 1939, **35**, 546.
[3] *Ibid.*, p. 1340. For a discussion on the validity of the method, see Dippy, and Jenkins, *ibid.*, 1941, **37**, 366, and Everett and Wynne-Jones, *ibid.*, p. 373.

Calculated ionic composition of catalysing solutions at 113·5° (*concentrations in g.-ions/l.*; k_{exp} *in* 10^5 *sec.*$^{-1}$).

Oxalic acid				*Phosphoric acid*			
Concn.				Concn.			
$[(CO_2H)_2]$	$[H^+]$ and $[HO_2C{\cdot}CO_2^-]$	k_{exp}	k_{exp}*	$[H_3PO_4]$	$[H^+]$ and $[H_2PO_4^-]$	k_{exp}	k_{exp}*
0·228	0·089	22·80	39·0	0·428	0·075	16·08	33·0
0·308	0·107	31·23	49·0	0·597	0·089	21·04	39·0
0·418	0·128	43·05	58·0	0·733	0·103	29·70	47·0
0·511	0·144	44·60	66·0	0·877	0·111	33·30	51·0

k_{exp}* is interpolated from the plot of $[H^+]$ against k_{exp} for monobasic acids.[1]

0·15 and there was no significant concentration of bivalent ions. We should, therefore, expect that the reaction rate would be identical with that obtained with strong monobasic acids at the same concentration of hydrogen ions, if the hydrogen ion were the sole catalysing species. It will be seen from the Table that systematically low values of k_{exp} are obtained. Agreement would be close if the acidity constants used in the calculation were about twofold too large. Such a discrepancy is quite possible, with phosphoric acid because of the large extrapolation (from 50° to 113·5°) and the method of calculation; and with oxalic acid owing to the use of an acidity constant quoted at 18° for calculation of hydrogen-ion concentrations at 113·5°. We conclude, therefore, that the observed reaction rates can be adequately explained by catalysis by hydrogen ions.

Non-catalysing acids. At 113·5° no reaction was detected with saturated ammonium chloride during 2 days; or with M-sodium dihydrogen phosphate or 0·1M-sodium hydrogen oxalate after 5 hr. From these results and those for phosphoric and oxalic acid it is clear that none of the species NH_4^+, $H_2PO_4^-$, HPO_4^{2-}, or $HO_2C{\cdot}CO_2^-$ catalyses the reaction significantly. It has also been shown that the bisulphate ion does not catalyse the reaction.[1] It would seem reasonable therefore to conclude that the pinacol–pinacone rearrangement is not subject to general acid catalysis.

CHEMISTRY DEPARTMENT, and TRACER ELEMENTS SECTION OF THE COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION, UNIVERSITY, MELBOURNE, AUSTRALIA.

[*Received, July 19th*, 1955.]

709. *Absorption Spectra of Ketones. Part V.* γ-Substituted αβ-Unsaturated Ketones.*

By C. W. BIRD, R. C. COOKSON, and S. H. DANDEGAONKER.

THE difference in absorption of light by equatorial and by axial 2-substituted *cyclo*hexanones in both the infrared [1,2] and the ultraviolet [3,4] region of the spectrum aroused our interest in the spectroscopic properties of geometrically analogous γ-substituted αβ-unsaturated ketones, typified by the epimeric 6-substituted cholest-4-en-3-ones (I).

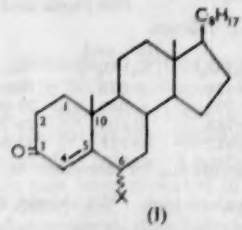
In the stable conformation of structure (I), C-1 lies below the plane occupied by C-2, C-3, C-4, C-5, C-6, C-10, and the oxygen atom. The relation of a 6α- and a 6β-substituent to the 4 : 5-double bond is then the same as that of an equatorial and an axial substituent to the carbonyl group of a 2-substituted *cyclo*hexanone [see partial formula (II)].

The increase in frequency of the carbonyl stretching vibration of a *cyclo*hexanone produced by introduction of an equatorial 2-bromine atom was attributed by Jones and his colleagues [1] to the reduction in the single-bond character of the C=O bond by the adjacent, almost co-planar, C–Br dipole, an effect that would be almost at a minimum for an axial bromine atom, which in fact has little influence on the frequency. Consistently with Jones's electrostatic field effect, introduction of a 6-bromine atom into cholestenone in either configuration only slightly affects the carbonyl frequency (Table 1). The slight increase in frequency produced by a 6-bromine atom may arise from its inductive pull

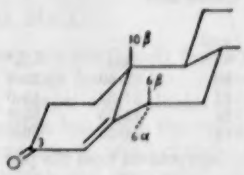
* Part IV, *J.*, 1956, 2302.

[1] Jones, Ramsay, Herling, and Dobriner, *J. Amer. Chem. Soc.*, 1952, **74**, 2828.
[2] Corey, *ibid.*, 1953, **75**, 2301, 3297; 1954, **76**, 175.
[3] Cookson, *J.*, 1954, 282.
[4] Cookson and Dandegaonker, *J.*, 1955, 352.

through the carbon chain. 6-Hydroxy- and 6-acetoxy-cholestenone absorb very near 1670 cm.$^{-1}$ regardless of the configuration of the oxygen atom.[5, 6, 7]



(I)



(II)

In carbon disulphide solution (potassium bromide prism) the 6α-bromide shows bands at 788 and 726 cm.$^{-1}$, and the 6β-bromide at 700 and 649 cm.$^{-1}$. Dr. J. E. Page tentatively assigns the first pair of bands to stretching of the equatorial C–Br bond and the second pair to the vibrations of the axial C–Br bond.[8]

Table 2 records the ultraviolet spectra of the ketones. The bathochromic effect of

TABLE 1.

	$\nu_{max.}$ (CS_2) (cm.$^{-1}$)		$\nu_{max.}$ (CS_2) (cm.$^{-1}$)
Cholest-4-en-3-one	1674	6α-Bromocholest-4-en-3-one...	1680
		6β-Bromo- ,, ...	1678

TABLE 2. *Absorption maxima.* (Wavelengths in mμ; ε in parentheses.)

	K-band (EtOH)	*R*-band (*n*-hexane) *E*	*D*	*C*	*B*	*A*
Cholest-4-en-3-one	241 (18,000)	314 (45)	323·5 (49)	336 (47)	349 (34)	367 (14)
6α-Chloro-	239 (19,000)	317 (45)	327 (45)	339 (41)	352 (31)	368 (15)
6β-Chloro-	241 (15,100)	327 (54)	338 (53)	350 (51)	364 • (40)	382 • (22)
6α-Bromo-	238 (15,800)	319 • (31)	329·5 (36)	340·5 (36)	352 • (28)	372 • (11·5)
6β-Bromo-	244 (13,700)	—	344 (64·5)	355 (62)	371 • (46·5)	391 • (20)
6α-Hydroxy-	240 (16,200)	314 • (30)	325·5 (36)	338 (36)	348·5 (26)	368·5 (9)
6β-Hydroxy-	236 (13,500)	—	331 (34)	342 (35)	356 (26)	375 (10·5)
6α-Acetoxy-	236 (16,600)	314 • (33)	325·5 (39)	338 (39)	350 (30)	370 (13)
6β-Acetoxy-	237 (12,600)	324 • (24)	334 (40)	346·5 (40)	361 (29)	380 (13)

• Inflection.

6β-bromine has been commented on previously,[9, 10] and can be attributed to the axial nature of the C–Br bond, which is almost ideally situated for interaction in the excited state, either by hyperconjugation of its σ-electrons, or by involvement of the *p*-electrons on the bromine atom with the π-electron system. For the equatorial 6α-epimer the possibility of interaction of both sorts is nearly at a minimum.

In ethanol the long-wavelength, $n \longrightarrow \pi$ band of the cholestenones appeared only as a broad, ill-defined maximum or inflection, that was unsuitable for analysis. But in hexane (Table 2) the band was easily resolved, and showed typical[11] vibrational fine structure. Substitution of an equatorial 6α-halogen atom into cholestenone moves the entire $n \longrightarrow \pi$ band to the red by only a few mμ. An axial 6β-halogen atom produces a much larger shift in the same direction. Each bromide absorbs more intensely than the corresponding chloride, and the absorption of the axial halide is stronger, and shows rather less fine structure, than that of the equatorial epimer.

The shapes of the extinction curves of all four 6-oxygenated ketones are very similar. Again, an equatorial substituent causes only a slight shift in wavelength, whereas an axial one causes a substantial shift to the red.

[5] Sondheimer, Kaufmann, Romo, Martinez, and Rosenkranz, *J. Amer. Chem. Soc.*, 1953, **75**, 4712.
[6] Romo, Rosenkranz, Djerassi, and Sondheimer, *J. Org. Chem.*, 1954, **19**, 1509.
[7] Fieser, *J. Amer. Chem. Soc.*, 1953, **75**, 4377.
[8] Cf. Barton, Page, and Shoppee, *J.*, 1956, 331.
[9] Barton and Miller, *J. Amer. Chem. Soc.*, 1950, **72**, 1066; Djerassi, Rosenkranz, Romo, Kaufmann, and Pataki, *ibid.*, p. 4534.
[10] Dorfman, *Chem. Rev.*, 1953, **53**, 71.
[11] Cookson and Dandegaonker, *J.*, 1955, 1651.

Table 3 shows the average shift in wavelength of corresponding vibrational maxima produced by substitution of cholestenone at position 6 by various groups, and, for

TABLE 3. $\Delta\lambda$ (mμ) *for ketones.*

Substituent	γ-Subst. αβ-unsat.		α-Subst. sat.[5,4]	
	e	a	e	a
Cl	+3	+14	− 5	+15 *
Br	+5	+20	− 5	+28
OH	+2	+ 7	−12	+17
OAc	+2	+10	− 5	+10

* 2-Chloro*cyclo*hexanone, with an axial chlorine atom, has $\lambda_{max.}$ 294 mμ (ε 24) in EtOH. Comparison with *cyclo*hexanone, $\lambda_{max.}$ 283 mμ (ε 16), gives a value of +11 mμ for $\Delta\lambda$, agreeing perfectly with that reported by Corey and Burke (*J. Amer. Chem. Soc.*, 1955, **77**, 5418), but rather less than $\Delta\lambda$ found recently [4] for two axial α-chloro*cyclo*hexanones in ring A of the steroids.

comparison, the shift in the maximum of a *cyclo*hexanone produced by the same substituents on the α-carbon atom. The figures do not run exactly parallel: one of the most striking contrasts is the reversal in the relative order of hydroxyl and acetoxyl in the two series.

Experimental.—Ultraviolet spectra were measured as before.[11] Infrared spectra were kindly determined by Glaxo Laboratories Ltd., Greenford, on a Perkin–Elmer 21, double-beam spectrophotometer with a potassium bromide prism. Rotations were measured at about 1—2% concentration in $CHCl_3$.

Cholest-4-en-3-one[12] had m. p. 80—81° $[\alpha]_D$ 92°; 6α-chlorocholest-4-en-3-one,[13] m. p. 121—122°, $[\alpha]_D$ 60°; 6α-bromocholest-4-en-3-one,[9] m. p. 113°, $[\alpha]_D$ 54°; the 6β-epimer,[9,14] m. p. 131°, $[\alpha]_D$ 7°; 6α-hydroxycholest-4-en-3-one,[5,7] m. p. 162°, $[\alpha]_D$ 87·5°; 6β-epimer,[5,6] m. p. 189—190°, $[\alpha]_D$ 31°; 6β-acetoxycholest-4-en-3-one,[5,6] m. p. 102—103°, $[\alpha]_D$ 38°. Samples of the other compounds were generously given by Professor D. H. R. Barton, F.R.S., Professor C. Djerassi, Professor L. F. Fieser, and Dr. F. Sondheimer.

BIRKBECK COLLEGE, LONDON, W.C.1. [*Received, March 19th, 1956.*]

[12] *Organic Syntheses*, 1941, **21**, 18.
[13] Barton and Miller, *J. Amer. Chem. Soc.*, 1950, **72**, 370.
[14] Fieser, *ibid.*, 1953, **75**, 5421.

---

710. *Synthesis of Tetramethylhydrazine by Photolysis and Pyrolysis of Tetramethyltetrazen.*

By J. S. WATSON.

TETRAMETHYLHYDRAZINE has proved difficult to prepare [1] and was only recently made by Aston and his co-workers [2] in somewhat small yield by the reduction of *sym.*-diformyldimethylhydrazine with lithium aluminium hydride. The method described below involves photolysis or pyrolysis of tetramethyltetrazen $(NMe_2{\cdot}N{:})_2$ which under favourable conditions yields as much as 40% of tetramethylhydrazine.

Previous work [3,4] has shown that tetra-arylhydrazines may be prepared by the thermal decomposition of the corresponding tetrazens. Wieland and Fresnel,[4] however, found products other than hydrazines when alkyl-aryl-substituted tetrazens were decomposed and from tetraethyltetrazen obtained only nitrogen, diethylamine, and a Schiff base. All these reactions were carried out in solution or in the liquid state. The only information [5] available on the thermal decomposition of tetramethyltetrazen is that it explodes at its boiling point, 130°/760 mm.

The present work describes a method whereby the vapour of tetramethyltetrazen at a pressure of 4 mm. and with a contact time of 10 sec. may be passed safely through a glass

[1] Klages, Naher, Kircher, and Bock, *Annalen*, 1941, **547**, 1.
[2] Class, Aston, and Oakwood, *J. Amer. Chem. Soc.*, 1953, **75**, 2937.
[3] Sidgwick, Taylor, and Baker, "The Organic Chemistry of Nitrogen," Oxford Univ. Press, 1949, pp. 390, 450.
[4] Wieland and Fresnel, *Annalen*, 1912, **392**, 135.
[5] Renouf, *Ber.*, 1880, **13**, 2173.

tube heated to about 300°, decomposing smoothly to nitrogen, tetramethylhydrazine, dimethylamine, and tris(methylmethyleneamine) $(CH_2{:}NMe)_3$, referred to below as "trimer." At 200° no decomposition takes place under these conditions. Photolysis of tetramethyltetrazen in liquid phase, in solution, or in the gas phase at 25° produces the same products. The quantum yield for production of nitrogen is about 0·9. Tetramethylhydrazine (b. p. 73°/760 mm.) may be easily separated by distillation from dimethylamine (b. p. 7°/760 mm.) and the " trimer " (b. p. 63°/25 mm.).

The above products lead one to believe that the reaction involves the production of free dimethylamino-radicals, some of which combine to form hydrazine while others disproportionate. The methylmethyleneamine subsequently polymerises to trimer.

$$Me_2N{\cdot}N{:}N{\cdot}NMe_2 \xrightarrow{h\nu} N_2 + 2Me_2N{\cdot}$$

$$2Me_2N{\cdot} \longrightarrow Me_2N{\cdot}NMe_2$$

$$2Me_2N{\cdot} \longrightarrow NHMe_2 + CH_2{:}NMe$$

It is possible that the trimer and dimethylamine may arise by abstraction of a hydrogen atom from the substrate, *e.g.*:

$$Me_2N{\cdot} + Me_2N{\cdot}N{:}N{\cdot}NMe_2 \longrightarrow NHMe_2 + {\cdot}CH_2{\cdot}NMe{\cdot}N{:}N{\cdot}NMe_2$$

$${\cdot}CH_2{\cdot}NMe{\cdot}N{:}N{\cdot}NMe_2 \longrightarrow CH_2{:}NMe + N_2 + NMe_2{\cdot}$$

but this seems unlikely, at least in photolysis, since a chain would be involved and the quantum yield is less than 1·0.

In addition to the products mentioned, there was a very small amount (1%, detected by the mass spectrometer) of *NNN'N'*-tetramethylmethylenediamine $Me_2N{\cdot}CH_2{\cdot}NMe_2$. This material boils at 83—85°/760 mm. and thus is difficult to separate from the hydrazine. Its origin is obscure, but it is of interest that it has also been found in the mercury-photosensitised decomposition of dimethylamine.[6]

Experimental.—Tetramethyltetrazen was prepared from unsymmetrical dimethylhydrazine by Renouf's method.[5] The hydrazine (10 g.) (dried over solid potassium hydroxide) in anhydrous ether (100 ml.) was treated under reflux with small quantities of mercuric oxide (either the yellow or the red variety is satisfactory). The ether boiled and a black precipitate, presumably mercury, was formed. When further addition of mercuric oxide caused no further reaction, the mixture was heated on a water-bath for 15 min., then cooled and filtered. The light yellow liquid was dried (K_2CO_3), evaporated, and distilled, yielding tetramethyltetrazen (5·5 g.), b. p. 44°/30 mm., $\lambda_{max.}$ 2800 Å (ε 14,000). A deep yellow residue remained.

Pyrolysis in flow system. Tetramethyltetrazen was stored as a liquid in a tube attached *via* a stopcock to a horizontal glass reaction vessel, 30 cm. long, 2·5 cm. in diameter, heated electrically to about 300°. The temperature was measured by a thermometer inserted in a well in the centre of the tube, and the pressure by a mercury manometer. The apparatus was evacuated continuously. The tetrazen was admitted as a vapour, at about 4 mm. After reaction the products flowed through a restricting capillary to two traps, one at −80° (solid carbon dioxide–acetone) and the other at −195° (liquid nitrogen). Uncondensable gas was removed continuously by the vacuum-pump. By weighing the storage tube before and after each experiment the weight of material passed, and consequently the contact time were obtained. The sample collected was weighed and fractionally distilled. Fractions obtained were as follows :

Uncondensable gas : A sample was examined mass spectroscopically and found to be pure nitrogen.

Liquid fractions : Fraction (1), condensable at −195°, but volatile at 25°, was shown by mass spectroscopy to be largely dimethylamine, but occasionally small amounts of monomethylamine were found. Dimethylamine was further characterised by its v. p. (2·8 mm. at 78°), b. p. (7°/760 mm.), picrate (m. p. 158°), and molecular weight (45). Fraction (2), b. p. 70—75°/760 mm., consisted of tetramethylhydrazine with small amounts of *NNN'N'*-tetramethylmethylenediamine and was analysed mass-spectroscopically. Two or three further fractionations gave pure tetramethylhydrazine, with a penetrating fish-like odour, b. p. 73°/760 mm.,

[6] Watson and Darwent, unpublished work.

n_D^{25} 1·4040 [Found : C, 53·5; H, 13·7; N, 31·8. Calc. for $C_4H_{12}N_2$: C, 54·5; H, 13·6; N, 31·8%. *M* (vapour), 87; parent peak from mass spectrum, 88], giving a carbon disulphide complex, m. p. 130°. Fraction (3), b. p. 63—66°/25 mm., essentially the " trimer " $(CH_2{\cdot}NMe)_3$, was identified by comparing it with an authentic specimen, and by its b. p. 64—65°/25 mm., n_D^{25} 1·4600, carbon disulphide complex, m. p. 102°, picrate, m. p. 118°, and the parent peak (129) from the mass spectrum.

In a typical experiment 4·15 g. of tetramethyltetrazen, pyrolysed at 300° at a flow rate of 0·65 g. per hr., gave dimethylamine 0·7 g., " trimer " 0·55 g., tetramethylhydrazine 1·3 g., residue 0·54 g., and no unchanged tetramethyltetrazen. In an experiment at 200° all the tetrazen was recovered unchanged in the traps.

Photolysis of liquid in a static system. Tetramethyltetrazen was placed in a quartz cell, of 35 ml. capacity, 5·6 cm. in diameter, and 2·5 cm. deep, illuminated on each side by two quartz low-pressure mercury lamps about 1 cm. from the cell faces. The whole was placed in water at about 25°. Attached to the cell was a condenser, which led by a tube to a trap containing N-hydrochloric acid to collect the dimethylamine produced, and thence to a trough, etc., tc collect and measure the uncondensable gas.

In a typical experiment 27 g. of the tetrazen were photolysed, nitrogen being evolved at the rate of about 20 ml./hr. After 10 days 4·7 l. had been produced, the light was then switched off. The acid solution was titrated and the contents of the cell fractionated as above. Products were nitrogen 5·9 g., dimethylamine 4·3 g., tetramethylhydrazine 6·0 g., " trimer " 4·0 g., unchanged tetramethyltetrazen 2·4 g., and residue 2·5 g. The quantum yield, measured by photolysing 0·5M-chloroacetic acid [7] at 25°, was 0·09 ± 0·05 for production of nitrogen. Experiments with a solution of the tetrazen in ether gave similar results except that fractionation was more difficult.

In a few experiments the pyrolysis and photolysis of the vapour of tetramethyltetrazen were investigated in a static system. At 25° the v. p. of tetramethyltetrazen is about 8 mm. and reactions were carried out at this pressure. Both the photochemical and the thermal decomposition were investigated in a quartz cell of 200 ml. capacity, enclosed in a furnace, and, for photolysis, illuminated by a quartz mercury lamp. Owing to the small quantities of material in these experiments, the products were analysed mass-spectroscopically. Photochemical decomposition was rapid at 25°, the pressure rising to over double its initial figure when all tetramethyltetrazen had reacted. Pyrolysis of the vapour was very slow at 150°; after 15 hr. the tetrazen had not completely decomposed; but at 280° the reaction was very rapid and was complete in a few minutes. In both cases the products were nitrogen, dimethylamine, tetramethylhydrazine, " trimer, " and traces of tetramethylmethylenediamine.

GENERAL RESEARCH ORGANISATION, OLIN MATHIESON CHEMICAL CORPORATION,
NEW HAVEN, CONNECTICUT, U.S.A. [*Received, April 3rd*, 1956.]

[7] Smith, Leighton, P. A., and Leighton, W. G., *J. Amer. Chem. Soc.*, 1939, **61**, 2299.

---

711. *The Preparation of the Half Esters of Phthalic Acid and of 3-Nitrophthalic Acid.*

By M. K. HARGREAVES.

IN the course of other work it became necessary to prepare the pentyl hydrogen 3-nitrophthalates. The original procedure [1] involved heating the neat alcohol with 3-nitrophthalic anhydride for some hours. Pickard and Kenyon prepared many hydrogen phthalates by a similar method,[2] which was later improved by carrying out the reaction in pyridine solution.[3] Balfe, Doughty, and Kenyon [4] found, however, that heating mixtures of 3-nitrophthalic anhydride and an alcohol in pyridine eliminates nitrogen dioxide with the production of a betaine derivative, but that 10% of dioxan inhibited this reaction.

Gerrard, Madden, and Tolcher [5] have shown that dioxan and pyridine have rather

[1] McKenzie, *J.*, 1901, **79**, 1135.
[2] Pickard and Kenyon, *J.*, 1907, **91**, 2058.
[3] Levene and Mikeska, *J. Biol. Chem.*, 1927, **75**, 594.
[4] Balfe, Doughty, and Kenyon, *J.*, 1953, 2470.
[5] Gerrard, Madden, and Tolcher, *J. Appl. Chem.*, 1955, **5**, 31

similar properties in other reactions. It is now found that dioxan can be substituted advantageously for pyridine in the preparation of esters of 2-methylbutanol; with secondary alcohols the advantage of a cleaner product is offset by the slower reaction. The function of the pyridine or dioxan may not be specific since in certain cases an improved product can be obtained by carrying out the reaction in equal parts of pyridine and toluene,[6] whilst in others the product can be obtained by refluxing in a low-boiling solvent such as chloroform;[7] it seems unlikely, however, to be merely that of solvent. Where effective, the substitution of dioxan for pyridine results in an improved product.

2-Methylbutyl hydrogen 3-nitrophthalate is readily formed during 2 hr. on the steam-bath, though longer heating increases the yield somewhat. On the other hand 2-methylbutyl hydrogen phthalate is less readily formed, and the *sec.*-butyl half-ester even less readily still.

Experimental.—*2-(±)-2′-Methylbutyl 1-hydrogen 3-nitrophthalate.*[8] (±)-2-Methylbutanol (4·4 g., 1 mol.), 3-nitrophthalic anhydride (9·7 g., 1 mol.), and dioxan (13·2 g., 3 mols.) were heated on the steam-bath for 2 hr. after solution was complete. After 2 days at room temperature the mixture was poured on ice–dilute hydrochloric acid. The pale buff crystals, which crystallised from the lower layer, were partly dried at the pump (yield, 14·6 g.) then dissolved in ether and extracted therefrom into saturated sodium hydrogen carbonate solution. The aqueous solution was poured on ice–dilute hydrochloric acid. The crystals (9·4 g., 67%) after two crystallisations from benzene had m. p. 156—156·5° (Found, by rapid titration with 0·1N-sodium hydroxide: *M*, 282. Calc. for $C_{12}H_{15}O_6N$: *M*, 281). 1-(±)-2′-Methylbutyl 2-hydrogen 3-nitrophthalate (10—20%) remained in the benzene mother-liquors.

(±)-2-Methylbutyl hydrogen phthalate. (±)-2-Methylbutanol (4·4 g.), phthalic anhydride (7·4 g., 1 mol.), and dioxan (13·2 g., 3 mols.) were treated as above except that the mixture was kept on the steam-bath for 2 days. The mixture was worked up as before but at each stage a liquid was obtained. The liquid ester after reprecipitation from the bicarbonate solution was dissolved in ether, the solution dried ($CaCl_2$), and the ether then removed. The remaining liquid crystallised after being cooled on solid carbon dioxide and worked up in light petroleum. The product (10·2 g., 86%) had m. p. 1—2°. After being reworked in cold petroleum 3·5 g. of material were obtained which remained solid overnight in a desiccator. Recrystallised twice from light petroleum the small rhombs had m. p. 36—37° (Found, by rapid titration with 0·1N-sodium hydroxide: *M*, 238. Calc. for $C_{12}H_{16}O_4$: *M*, 236).

isoPentyl hydrogen phthalate. *iso*Pentanol (8·8 g., 1 mol.), phthalic anhydride (14·8 g., 1 mol.), and dioxan (26·4 g., 3 mols.) were heated and the product worked up as described above. The crystals (7·6 g., 56%) had m. p. 36·5—37·5° after two recrystallisations from light petroleum (Found, by rapid titration with 0·1N-sodium hydroxide: *M*, 239. Calc. for $C_{13}H_{16}O_4$: *M*, 236).

sec.-Butyl hydrogen phthalate. A warm mixture of (±)-*sec.*-butyl alcohol (18·5 g.), phthalic anhydride (37 g., 1 mol.), and dioxan (66 g., 3 mols.) was shaken until solution was complete and then heated overnight. On cooling crystals formed and heating was therefore continued for a further 2 days; crystals did not then appear on cooling. The mixture was worked up as before. After the dried ethereal solution had been treated with petroleum the product was recrystallised from light petroleum and then had m. p. 59—60° (corr.) (yield: 31 g., 56%) (Found, by rapid titration with 0·1N-sodium hydroxide: *M*, 221. Calc. for $C_{12}H_{14}O_4$: *M*, 222). Pickard and Kenyon[9] give m. p. 56—57°.

The alcohols used were commercial products dried over fresh quick-lime, and distilled. Dioxan was refluxed over sodium for several days and then distilled. Phthalic anhydride was a commercial product which was free from phthalic acid.

Thanks are due to the Central Research Fund Committee of the University of London for grants and to Professor H. Burton for facilities.

QUEEN ELIZABETH COLLEGE (UNIVERSITY OF LONDON),
LONDON, W.8.

[*Received, April 5th*, 1956.]

[6] Balfe, Hargreaves, and Kenyon, *J.*, 1951, 584.
[7] Pickard and Kenyon, *J.*, 1914, **105**, 1115.
[8] Cohen, Marshall, and Woodman, *J.*, 1915, **107**, 887.
[9] Pickard and Kenyon, *J.*, 1911, **99**, 63.

712. *The Viscosities of Iodine Pentafluoride and Ditellurium Decafluoride.*

By G. Hetherington and P. L. Robinson.

To the relatively few viscosities of inorganic fluorides available (those of hydrogen fluoride,[1] arsenious and antimonic fluorides,[2] uranium hexafluoride,[3] chlorine trifluoride,[4] and nitryl fluoride [5]) we now add those of iodine pentafluoride and ditellurium decafluoride.

The method was essentially that used in our nitryl fluoride determination [5] except for a slight modification of the Ostwald-type viscometer. The viscosities of iodine pentafluoride (Table 1) cover a temperature range from 14·55° and 69·30° and by solving the

Table 1. *Viscosities, η(mP), of iodine pentafluoride.*

Temp.	η, Obs.	η, Calc.	Δη	100(Δη)²	Temp.	η, Obs.	η, Calc.	Δη	100(Δη)²
14·55°	26·66	26·82	−0·16	2·56	48·75°	14·30	14·28	+0·02	0·04
25·00	21·11	21·11	0·00	0·00	62·75	12·01	12·01	0·00	0·00
34·30	17·84	17·80	+0·04	0·16	69·30	11·17	11·19	−0·02	0·04

Table 2. *Viscosities of ditellurium decafluoride.*

−30·0°	2·542	2·513	+0·029	0·08	18·2°	1·209	1·215	−0·006	0·00
−23·0	2·210	2·192	+0·018	0·03	25·0	1·140	1·127	+0·013	0·02
−11·0	1·791	1·786	+0·005	0·00	32·2	1·053	1·045	+0·008	0·01
0·0	1·533	1·524	+0·009	0·01	44·9	0·930	0·925	+0·005	0·00

equation of the absolute viscosity–temperature curve, $\eta_t = \eta_0/(1 + At + Bt^2)$ with values from the smoothed curve, it was found that $A = 0{\cdot}04231$, $B = -0{\cdot}000014$, and $\eta_0 = 0{\cdot}04325$ P. The temperature range for ditellurium decafluoride (Table) is from −30·0° to 44·9° and the constants for the above equation are $A = 0{\cdot}01365$, $B = 0{\cdot}0000175$, and $\eta_0 = 0{\cdot}01524$ P.

Experimental.—The apparatus was a slightly modified form of the viscometer previously used by us for nitryl fluoride.[5] The diagram of the viscometer in that communication being referred to, the socket *P* and tap *Q* were replaced by a Y-piece carrying a "break-seal" joint, and a "run-through" joint connected to the sample under investigation. These were for emptying and filling the viscometer, respectively, and were preferred to the original arrangement since they enable contact between the fluoride and fluorocarbon grease to be avoided throughout. After being charged, the apparatus was sealed below the "run-through" joint and the filling device removed. Apart from this change in the mode of introducing the weighed sample of the fluoride, the previous procedure was followed. No difficulty attended the weighing of the fluoride specimens as both are liquids at the ordinary temperature.

The iodine pentafluoride was prepared by burning iodine in a stream of fluorine diluted with nitrogen and purified by bulb-to-bulb distillation in vacuum with rejection of adequate head and tail fractions. The ditellurium decafluoride had been prepared by Campbell and Robinson [6] whose work also furnished the density data used.

The authors thank Imperial Chemical Industries Limited, General Chemicals Division, Widnes, for the use of the fluorine cell. This work was carried out during the tenure of a Salters' Fellowship (G. H.).

King's College, Newcastle upon Tyne, 1. [*Received, April 9th,* 1956.]

[1] Simons and Dresdner, *J. Amer. Chem. Soc.*, 1944, **66**, 1070.
[2] Woolf and Greenwood, *J.*, 1949, 2861.
[3] Llewellyn, *J.*, 1953, 28.
[4] Banks, Davies, and Rudge, *J.*, 1953, 732.
[5] Hetherington and Robinson, *J.*, 1955, 2230.
[6] Campbell and Robinson, *J.*, in the press.

713. *Bitter Principles of the Cucurbitaceae. Part IV.* Dehydrogenation of Cucurbitacin A.*

By P. R. Enslin and D. E. A. Rivett.

Recently a group of related crystalline bitter principles, the cucurbitacins A, B, C, and D, has been isolated in these laboratories from various Cucurbitaceae.[1] They all possess an αβ-unsaturated keto-group. Cucurbitacin A, $C_{28}H_{40}O_8$, also contains two further keto-groups, an acetoxy- and three hydroxy-groups. We now report the dehydrogenation of cucurbitacin A which has been reduced with lithium aluminium hydride.

Zinc dust distillation and selenium dehydrogenation of the closely related elaterin, $C_{28}H_{38}O_7$, were both reported to give 1 : 4-dimethylnaphthalene [2,3] which, however, was insufficiently characterised. From the dehydrogenation of reduced cucurbitacin A, we failed to obtain any simple alkylnaphthalenes but isolated 1 : 2 : 8-trimethylphenanthrene and an unidentified phenanthrene. This indicates a possible structural relation to the diterpenes and tetracyclic triterpenes.

For the separation of the dehydrogenation mixture, we used adsorption on alumina followed by reversed-phase partition chromatography.[4] We believe this technique to be of wide applicability in the separation of the complicated mixtures obtained on dehydrogenation of natural products.

Experimental.—Unless otherwise stated, ultraviolet absorption spectra were measured in 96% EtOH with a Beckman D.U. spectrophotometer. The infrared spectrum was measured on a Perkin–Elmer Model 21 spectrophotometer. M. p.s are corrected.

Reduction of cucurbitacin A with lithium aluminium hydride. Cucurbitacin A (10 g.), dissolved in tetrahydrofuran (40 ml.), was reduced by lithium aluminium hydride (5 g.) in ether (1 l.) for 5 hr. under reflux. Decomposition with absolute ethanol (500 ml.) and 8N-sulphuric acid (65 ml.) precipitated most of the salts. The supernatant solution was dried and neutralised over anhydrous potassium carbonate. Evaporation afforded a white foam (9 g.) which showed no specific ultraviolet absorption.

Dehydrogenation of reduced cucurbitacin A. Reduced cucurbitacin A (18 g.) and selenium powder (18 g.) were heated together in four sealed tubes at 330° for 60 hr. Ether-extraction of the product gave a brown gum (4·5 g.). The pentane-soluble portion of this (2·9 g.) was chromatographed on alumina (Peter Spence, 100 g.) to give : (*a*) pentane eluate (0·67 g.), (*b*) pentane–benzene (9 : 1) eluate (0·29 g.), and (*c*) pentane–benzene (1 : 1) eluate (0·55 g.).

Fractions (*a*), (*b*), and (*c*) were separately rechromatographed and all fractions with similar ultraviolet spectra were combined. In this manner the following three fractions were obtained : (I) benzenoid fraction (0·26 g.), $\lambda_{max.}$ 269 and 277 mμ (in octane) ; (II) naphthenoid fraction (0·36 g.), $\lambda_{max.}$ 232 and 282 mμ (in octane) ; (III) phenanthrenoid fraction (0·27 g.), $\lambda_{max.}$ 259—262, 301—308, and 336—340 mμ.

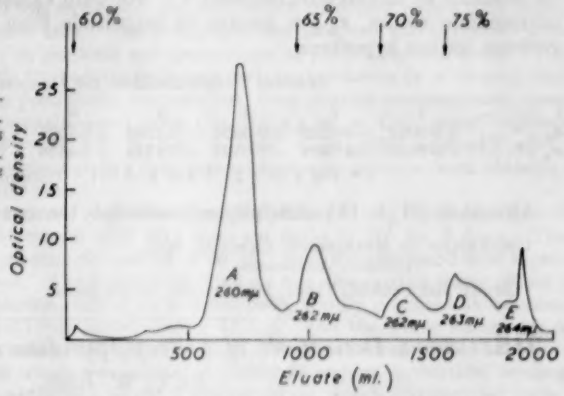
Fraction (III) was rechromatographed and a middle semi-solid fraction (IV) collected, having $\lambda_{max.}$ 261—262, 233, 294, 306—308, and 338—340 mμ. From the general shape of the ultraviolet absorption curve, it was clear that fraction (IV) was still a mixture and further separation was effected by reversed-phase partition chromatography.

Fraction (IV) (0·06 g.) was deposited on non-wetting kieselguhr and packed on top of a column (0·9 × 60 cm.) of non-wetting kieselguhr, impregnated with heptane (9 ml./8 g.), and the column was eluted with aqueous-ethanolic solutions (saturated with heptane) of increasing alcoholic strength.[4] The results are presented in the Figure. Fractions *A* and *B* were diluted with water and extracted with pentane. The crystalline residue (17·6 mg.), m. p. 119—131°, from fraction *A* was recrystallised from 96% ethanol to afford plates (9·4 mg.), m. p. 132—138°, which gave a 1 : 3 : 5-trinitrobenzene adduct, m. p. 189—190° (Found : C, 63·4 ; H, 4·4. Calc. for $C_{28}H_{19}O_6N_3$: C, 63·7 ; H, 4·4%) undepressed by authentic 1 : 2 : 8-trimethylphenanthrene 1 : 3 : 5-trinitrobenzene derivative. This material was decomposed on alumina to give 1 : 2 : 8-trimethylphenanthrene, m. p. and mixed m. p. 143—144° after two recrystallisations from methanol, $\lambda_{max.}$ 255, 261, 283, 294, 306, 322, 338, and 354 mμ (ε 43,800, 53,000, 10,800, 10,200, 12,100, 400, 370, and 150 respectively). The residue (9·6 mg.) from fraction B gave, after

* Part III, *J. Sci. Food Agric.*, 1956, **7**, in the press.

[1] Enslin, *J. Sci. Food Agric.*, 1954, **5**, 410.
[2] Moore, *J.*, 1910, **97**, 1801.
[3] Reichel and Eisenlöhr, *Annalen*, 1937, **531**, 287.
[4] Enslin and Rivett, *Chem. and Ind.*, 1956, 23.

another application of reversed-phase partition chromatography one main peak from which a partially crystalline substance (6·7 mg.) was isolated. This material on distillation at 100—110°/10^{-2} mm. afforded an oil, $\lambda_{max.}$ 261, 284, 296, 308, and 340 mμ (ε 50,900, 9900, 8700, 9700, and 860 respectively) which gave a 1 : 3 : 5-trinitrobenzene adduct, m. p. 196—198°. On decomposition of the trinitrobenzene derivative on alumina a crystalline hydrocarbon, m. p. 115—118°, was obtained after two recrystallisations from methanol. The infrared spectrum (in CS_2) showed strong bands at 853, 822, 809, and 776 cm.$^{-1}$. From its ultraviolet spectrum and position on the chromatogram this product appears to be a tetrasubstituted phenanthrene.[4,5] The physical properties of this phenanthrene and of its trinitrobenzene adduct do not correspond to those of any known tetra-alkylphenanthrene.



Separation of fraction (IV) *by reversed-phase partition chromatography. Changes of solvent* (% *v/v of aqueous ethanol*) *are indicated by arrows. Optical densities were measured at the wavelengths indicated.*

No pure substances could be obtained from fraction (II) by reversed-phase partition chromatography. The main chromatographic fractions ($\lambda_{max.}$ 234 and 284 mμ in octane) failed to form crystalline picrates and are considered to consist of incompletely dehydrogenated material. Fractions (I) and (II) were therefore combined and again dehydrogenated, this time at 400° for 48 hr. From the resulting mixture of phenanthrenes no identifiable substances could be isolated.

We thank Dr. O. Jeger and Mr. W. Manser (E.T.H., Zürich) for mixed m. p. determinations with their authentic phenanthrene derivatives, and for microanalyses, and Mr. P. K. Faure for the infrared spectrum. This Note is published with the permission of the South African Council for Scientific and Industrial Research.

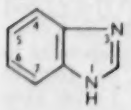
National Chemical Research Laboratory,
South African Council for Scientific and Industrial Research,
Pretoria, South Africa. [*Received, April 30th*, 1956.]

[5] Heilbronner, Däniker, and Plattner, *Helv. Chim. Acta*, 1949, **32**, 1723.

714. *Further Substitution in 5-Substituted Benziminazoles.*

By R. D. Brown and M. L. Heffernan.

Electrophilic reagents attack the benziminazole molecule (I) preferentially in the 5-position.[1] If then a $C_{(5)}$-substituent does not influence the course of further substitution, the new substituent would be expected to enter at the 6-position. In some cases this is the observed position of attack by electrophilic reagents, *e.g.* in nitration of 5-methyl-[2] and 5-methoxy-benziminazole.[3] However, when the substituent at the 5-position is the amino- or hydroxy-group the position of preferential attack is $C_{(4)}$.[4] It thus appears that an electron-releasing substituent at $C_{(5)}$ activates the 4-position to a greater extent than the 6-position. The order of electron release from the substituents mentioned above is [5] $NH_2 > OH > MeO > Me$ and apparently the *ortho*-activating effect of the first two



(I)

[1] Brown and Heffernan, *J.*, in the press.
[2] Fischer and Hess, *Ber.*, 1903, **36**, 3971.
[3] Ochiai and Kataga, *J. Pharm. Soc. Japan*, 1940, **60**, 543.
[4] Fries, *Annalen*, 1927, **454**, 121
[5] Ingold, "Structure and Mechanism in Organic Chemistry," Cornell U.P., 1953, p. 805.

substituents is so great that the preferential activation of the 4-position as compared with the 6-position is sufficient to outweigh the inherent greater reactivity at the 6-position in unsubstituted benziminazole.

In the molecular-orbital theory the extent of transmission of electronic effects from one position, μ, to another, ν, in a conjugated system is measured by the magnitude of the mutual polarizability, $\pi_{\mu,\nu}$. To test theoretically this hypothesis of preferential transmission to the 4-position we have calculated the mutual polarizabilities for benziminazole. The results are given in the accompanying table for two different values of the nitrogen electronegativity parameter, h, which cover the range of values likely to be appropriate for the molecule in various environments.[1,6] For both values of h and doubtless therefore for intermediate values, $\pi_{5,4}$ is greater in magnitude than $\pi_{5,6}$ thus providing theoretical evidence for our hypothesis.

Mutual Polarizabilities for Benziminazole.

ν	1	2	3	4	5	6	7	8	9
$\pi_{5,\nu}$ [a] ...	+0·0092	−0·0200	+0·0036	−0·1780	+0·4028	−0·1244	+0·0216	−0·0840	−0·0272
$\pi_{5,\nu}$ [b] ...	−0·0420	−0·0804	−0·0824	−0·1324	+0·4356	−0·0688	+0·0296	−0·0028	−0·0572

[a] For $h = +1$. [b] For $h = -1$. Both in units of $1/\beta$.

One of us (M. L. H.) gratefully acknowledges the award of a C.S.I.R.O. studentship.

UNIVERSITY OF MELBOURNE, CARLTON, N.3,
VICTORIA, AUSTRALIA.

[*Received, May 7th,* 1956.]

[6] Brown and Penfold, *Trans. Faraday Soc.*, in the press.

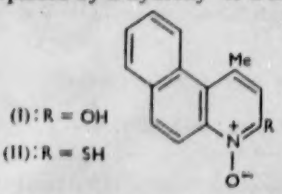
---

715. *Some Derivatives of 4-Propylpyridine and 5 : 6-Benzoquinoline.*

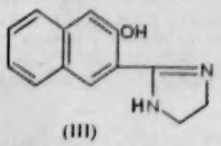
By C. W. REES.

8-HYDROXYQUINOLINE exerts its antibacterial action by combining with iron present in the medium, and the chelate is the true bactericidal agent.[1,2] Another powerful antibacterial, 2-mercaptopyridine 1-oxide,[3] is also a chelating agent. To demonstrate that its mode of action is similar to that of 8-hydroxyquinoline,[4] other lipophilic analogues have been prepared.

2-Chloro-4-methyl-5 : 6-benzoquinoline [5] was converted into the *N*-oxide, and the chlorine atom replaced by a hydroxy- or a mercapto-group, giving compounds (I) and (II)



(I): R = OH
(II): R = SH



(III)

respectively. Likewise 2-mercapto-4-*n*-propylpyridine 1-oxide was prepared from 2-bromo-4-propylpyridine. 4-*n*-Propylpicolinhydrazide was obtained from the acid [6] by way of the ethyl ester. 4 : 5-Dihydro-2-(3-hydroxy-2-naphthyl)glyoxaline (III) was also synthesized.

Experimental.—*5 : 6-Benzoquinolines.* 2-Chloro-4-methyl-5 : 6-benzoquinoline [5] (7·8 g.) and a solution of perbenzoic acid (1·2 equiv.) in chloroform (150 ml.) were set aside at 20° for 9 days. After extraction with 2N-sodium carbonate (3 × 50 ml.) the organic solution was evaporated to dryness and the residue was extracted continuously with light petroleum (b. p. 80—100°) to remove starting material. The residue of *2-chloro-4-methyl-5 : 6-benzoquinoline 1-oxide* gave colourless crystals (3·3 g., 40%), m. p. 208°, from ethanol (200 ml.; then concentrated) (Found : C, 69·4; H, 4·4; Cl, 14·85. $C_{14}H_{10}ONCl$ requires C, 69·0; H, 4·1; Cl, 14·55%).

[1] Albert, Gibson, and Rubbo, *Brit. J. Exp. Path.*, 1953, **34**, 119.
[2] Albert, Hampton, Selbie, and Simon, *ibid.*, 1954, **35**, 75.
[3] Shaw, Bernstein, Losee, and Lott, *J. Amer. Chem. Soc.*, 1950, **72**, 4362.
[4] Albert, Rees, and Tomlinson, unpublished work.
[5] Albert, Brown, and Duewell, *J.*, 1948, 1288.
[6] Solomon, *J.*, 1946, 934.

This oxide (1·4 g.) and 5N-sodium hydroxide were triturated together, then heated under reflux for 8 hr., diluted with boiling water to 250 ml. and filtered immediately, to remove starting material. Trishydroxymethyl-aminomethane (2 g.) was added as a buffer and the pH adjusted to 8·5 with sulphuric acid. After chilling, the precipitate of 2-hydroxy-4-methyl-5 : 6-benzoquinoline was filtered off and discarded. The filtrate, adjusted to pH 2, gave ***2-hydroxy-4-methyl-5 : 6-benzoquinoline* 1-*oxide*** **(I)** (0·4 g.) which, recrystallized from butan-1-ol, had m. p. 248° (Found : C, 74·7; H, 5·2; N, 6·1. $C_{14}H_{11}O_2N$ requires C, 74·7; H, 4·9; N, 6·2%). The product gives a deep red colour with aqueous ferric chloride; its solubility in boiling water is 10^{-4} mole/l.

A freshly prepared 4N-aqueous sodium hydrogen sulphide (1 equiv.) was added, during 1 hr., to 2-chloro-4-methyl-5 : 6-benzoquinoline 1-oxide (2 g.) in boiling ethanol (40 ml.), with stirring. After a further 30 min. the ethanol was recovered, and the residue triturated with a little water and adjusted to pH 2 with sulphuric acid. The precipitate was removed and extracted with cold N-sodium hydroxide (100 ml.; in portions) and precipitated at pH 2 (sulphuric acid). The precipitate was then extracted with 2% sodium hydrogen carbonate solution (4 × 50 ml.), and the extract adjusted to pH 2. This precipitate, recrystallized from acetone (concentrated), gave yellow *2-mercapto-4-methyl-5 : 6-benzoquinoline* 1-*oxide* (II) (0·2 g.), m. p. 173°, which oxidizes readily when moist (Found : C, 68·8; H, 4·5; N, 5·8; S, 13·5. $C_{14}H_{11}ONS$ requires C, 69·7; H, 4·6; N, 5·8; S, 13·3%). The product gives a deep green colour with aqueous ferric chloride; its solubility in boiling water is $<10^{-4}$ mole/l.

2-Mercapto-4-n-propylpyridine 1-*oxide*. 2-Bromo-4-propylpyridine [6] (10 g.) and a solution of perbenzoic acid (1·2 equiv.) in chloroform (127 ml.) were set aside at 20° for 5 days. The solution was extracted with 6N-hydrochloric acid (4 × 50 ml.), and the combined acid layers were taken to dryness at 90°/20 mm. The residual oil (10·8 g.) was dissolved in water (25 ml.) and adjusted to pH 6. To this solution, stirred on a steam-bath, freshly prepared 4N-aqueous sodium hydrogen sulphide (23·5 ml.) was added during 45 min., and the whole stirred for a further 45 min. The solution was cooled, taken to pH 2 (H_2SO_4), and extracted with chloroform. Recovery of the solvent left an oil which was extracted with 0·2N-sodium hydroxide, leaving undissolved sulphur. Chloroform-extraction at pH 2 yielded an oil, which was distilled under nitrogen at 110—140°/0·08 mm., and then fractionated to give pale yellow *2-mercapto-4-n-propylpyridine* 1-*oxide*, b. p. 94—96°/0·01 mm., n_D^{23} 1·6090 (Found : C, 57·2; H, 6·45; N, 8·3. $C_8H_{11}ONS$ requires C, 56·8; H, 6·55; N, 8·3%). It gives a deep purple colour with ferric chloride.

4-n-*Propylpicolinhydrazide*. 4-Propylpicolinic acid [6] (1·5 g.), fresh silver oxide (1·05 g.), ethyl iodide (1·42 g.), and dry xylene (8 ml.) were heated under reflux gently for 30 min. The mixture was filtered and the solid extracted with xylene. The xylene was recovered from the combined filtrates, and part of the residual *ethyl* 4-n-*propylpicolinate* (an oil; 1·6 g.) was converted in water into the *picrate*, which, recrystallized from 1 : 1 benzene–light petroleum, had m. p. 80° (Found : C, 48·5; H, 4·2; N, 13·35. $C_{17}H_{18}O_9N_4$ requires C, 48·35; H, 4·3; N, 13·3%). Hydrazine hydrate (90%; 0·8 g.) was added to the above ester (1·35 g.) in ethanol (15 ml.), and the whole set aside for 4 days at 20°. The volatile materials were distilled and the residual oil dried *in vacuo* at 20°, giving 4-*n*-propylpicolinhydrazide (1·24 g.) which formed a *picrate* [made in water and recrystallized from benzene (70 parts)], m. p. 111° (Found : C, 44·1; H, 3·8; N, 20·6. $C_{15}H_{16}O_8N_6$ requires C, 44·1; H, 3·95; N, 20·6%), and a ***hydrochloride*** (dry acid in ethanol, followed by ether; recrystallized from 1 : 1 ethanol–ether), m. p. 200—201° (Found, for material dried at 60°/0·005 mm. over phosphoric oxide : C, 46·1; H, 6·0; O, 7·2; N, 18·1; Cl, 22·4. $C_9H_{13}ON_3,1{\cdot}5HCl$ requires C, 46·2; H, 6·2; O, 6·8; N, 18·0; Cl, 22·7%).

4 : 5-Dihydro-2-(3-hydroxy-2-naphthyl)glyoxaline (III). 3-Hydroxy-2-naphthamide [7] (4·5 g.) and ethylenediamine (1·6 ml., 1 mol.) were heated at 140° for 1·5 hr. and then at 180° for 1·5 hr. Ammonia and water were evolved and the mixture slowly reddened and set solid. The volatile fractions were removed at 180°/20 mm., and the remaining solid (5·0 g.) was crystallized twice from ethanol (60 parts), giving bright yellow crystals of the *naphthol* (3·0 g.), m. p. 222°, sublimed at 150°/0·01 mm. (Found : C, 73·5; H, 5·7; N, 12·9. $C_{12}H_{12}ON_2$ requires C, 73·6; H, 5·7; N, 13·2%). The product gives a green colour with aqueous ferric chloride; it is readily soluble in N-hydrochloric acid, difficultly soluble in N-sodium hydroxide, and its solubility in water is 5×10^{-4} mole/l. at 20°.

The author thanks Professor A. Albert for his constant interest and advice.

THE DEPARTMENT OF MEDICAL CHEMISTRY,
THE AUSTRALIAN NATIONAL UNIVERSITY,
183, EUSTON ROAD, LONDON, N.W.1.
[Present address : BIRKBECK COLLEGE, LONDON, W.C.1.]

[*Received, May 14th*, 1956.]

[7] Lesser, *Ber.*, 1925, **58**, 210.

716. *The Janovsky Reaction.*

By M. J. Newlands and F. Wild.

Development of colour in the well-known reaction [1] between sodium hydroxide and an acetone solution of *m*-dinitrobenzene or of 3 : 5-dinitrobenzoic acid is considered to be limited [2] to derivatives of the former. The wavelength of maximum absorption of the colours produced by a group of *m*-dinitrobenzene derivatives has been measured; other polynitro-aromatic compounds have also been investigated. The results (see Table) suggest that the production of a colour is not restricted to *m*-dinitrobenzene derivatives.

Experimental.—The polynitro-aromatic compounds were dissolved in acetone and their absorption curves determined with a Unicam SP.350 spectrophotometer. 10% Aqueous sodium hydroxide was then added to the acetone solution; the mixture was well shaken and the new absorption curve investigated.

Compound	Colour	$\lambda_{max.}$ (mμ)
1-Fluoro-2 : 4-dinitrobenzene	Greenish-blue	430 and 550
1 : 3-Difluoro-4 : 6-dinitrobenzene	Deep blue	420 and 580
1 : 3-Dichloro-4 : 6-dinitrobenzene	Deep blue	640
1 : 3-Dibromo-4 : 6-dinitrobenzene	Deep blue	615
2 : 4-Dinitrophenetole	Reddish violet	560
2 : 4-Dinitrobenzenesulphonic acid	Rose	490
2 : 4-Dinitroaniline	Red	560
2 : 4-Dinitrodiphenylamine	Red	590
N-2′-Hydroxyethyl-2 : 4-dinitroaniline	Red	—
2 : 4-Dinitrophenylhydrazine	Blood red	570
2-Chloro-1 : 6-dinitronaphthalene	Red	510
2 : 7-Dinitrofluorenone	Red-violet	485
4 : 5-Benzothiazol-2-yl 4 : 8-dinitronaphthyl sulphide	Red	425 and 535
N-Methylimide of 3 : 6-dinitronaphthalene-1 : 8-dicarboxylic acid	Red violet	450 and 570

We thank Imperial Chemical Industries Limited (General Chemicals Division) for the three 1 : 3-dihalogeno-4 : 6-dinitrobenzenes and the Dyestuffs Division for the last four compounds.

Cambridge University Medical School, Tennis Court Road, Cambridge. [*Received, May 17th*, 1956.]

[1] Mann and Saunders, "Practical Organic Chemistry," Longmans, Green and Co., London, 1952, 3rd Edn., pp. 216, 261, 293.
[2] Hickinbottom, "Reactions of Organic Compounds," Longmans, Green and Co., London, 1948, 2nd Edn., p. 353.

---

717. *The Effect of Solvent on the Rates of Solvolysis of 1 : 2-Dichloro-2-methylpropane and of 3-Chloro-2-methylpropene, and the Rearrangement of the Latter Chloride in Formic Acid.*

By P. B. D. de la Mare, K. Leffek, and Adib Salama.

In unimolecular solvolysis of alkyl halides, change in solvent from ethanol towards water accelerates substitution, often by a factor of 10^5 or more over the extremes of the range. In bimolecular substitution this factor is usually much smaller. Very few measurements have been recorded which define with certainty the rates of hydrolysis in water of halides which are known to react unimolecularly. A value for *tert.*-butyl chloride has been estimated [1] by extrapolation of data obtained in mixtures of acetone and water; and an approximate kinetic measurement has been made for the solvolysis in water of 3-chlorobut-1-ene.[1] These are included in Table 1, together with values from the literature for methyl bromide [2] and *n*-propyl chloride,[3] typical of compounds which react bimolecularly in aqueous ethanolic solvents. Relative rates [2,3] for solvolysis in slightly aqueous formic acid are also included.

[1] Grunwald and Winstein, *J. Amer. Chem. Soc.*, 1948, **70**, 847.
[2] Winstein, Grunwald, and Jones, *ibid.*, 1951, **73**, 2700.
[3] Vernon, *J.*, 1954, 423, 4462.

In an earlier paper, a value was recorded [4] for the solvolysis of 1 : 2-dichloro-2-methylpropane in water. Values are now recorded for mixtures of ethanol and water, and for formic acid, as solvents; and the hydrolysis of 3-chloro-2-methylpropene has also been studied in water. These values are given in Table 2 as initial first-order rate-coefficients

TABLE 1. *Relative rates for the solvolysis of some halides.*

Compound :	MeBr	Pr^{n}Cl	Bu^{t}Cl	Me·CHCl·CH$_2$·CH$_3$
Temperature :	50°	101·6°	25°	25°
Rel. k_1 (EtOH)	0·07	0·04	0·00026	0·0008
Rel. k_1 (80% EtOH)	0·39	—	0·025	—
Rel. k_1 (50% EtOH) *	1·0	1·0	1·0	1·0
Rel. k_1 (H$_2$O)	1·8	—	90	71
Rel. k_1 (H·CO$_2$H)	—	0·05	3·0	1·5

* For each compound the rate of solvolysis in 50% EtOH is taken as standard.

TABLE 2. *Relative* rates of solvolysis of 1 : 2-dichloro-2-methylpropane, and of 3-chloro-2-methylpropene.*

Compound :	CMe$_2$Cl·CH$_2$Cl	CH$_2$:CMe·CH$_2$Cl
Temperature :	45°	45°
Rel. k_1 (EtOH)	—	0·032
Rel. k_1 (80% EtOH)	0·12	—
Rel. k_1 (50% EtOH)	1·0	1·0
Rel. k_1 (H$_2$O)	56	5·3
Rel. k_1 (H·CO$_2$H)	1·9	0·0067

* See footnote to Table 1.

(k_1), calculated for the liberation of one mole of chloride ion per mole of dichloride. Included also are values recorded by Vernon [3] for the solvolysis of the latter compound in ethanol, mixtures of ethanol and water, and formic acid.

With regard, first, to the solvolysis of 1 : 2-dichloro-2-methylpropane, bimolecular (S_N2) substitution in this compound under any of the conditions used in this work is highly improbable for steric reasons. Bimolecular elimination would be expected to yield 1-chloro-2-methylpropene, with liberation of one equivalent of chloride ion per mole of dichloride. Unimolecular substitution has been shown [4] to be the dominant mechanism in water, and is the probable mechanism even in 80% ethanol, in view of the liberation, as in water, of a few per cent. of additional chloride per mole of starting material, as established by Brown, Kharasch, and Chao.[5] It is presumed, therefore, that in the intermediate solvents, and in formic acid, the solvolysis of 1 : 2-dichloro-2-methylpropane is unimolecular.

From related considerations, Vernon [3] deduced that solvolysis of 3-chloro-2-methylpropene in ethanol and in mixtures of ethanol and water is substantially bimolecular. The same is almost certainly true for the solvent water (Table 2), in which the reaction is enormously faster than the solvolysis, presumed to be unimolecular,[3] in formic acid. The marked contrast, shown in Table 1, in the effect of solvent on the rate of solvolysis of compounds reacting by unimolecular (S_N1) and bimolecular (S_N2) mechanisms, is maintained in the new results recorded in Table 2, and it is possible that for relatively unreactive halides, such as those now investigated, comparisons involving the more aqueous media may sometimes be convenient, in that they bring the reactivities into a region accessible at moderate temperatures.

The olefinic products formed in the solvolysis of 1 : 2-dichloro-2-methylpropane in slightly aqueous formic acid were found to contain a ratio of allylic to vinylic chloride of 0·1, the former being estimated by reaction with aqueous-ethanolic silver nitrate. This result, at first sight surprising in view of the quite different ratio found for reactions in water,[4] can be understood, since we have also shown that the allylic chloride, if formed, would isomerise under the conditions used in the solvolysis, giving the equilibrium mixture :

$$CH_2{:}CMe{\cdot}CH_2Cl + H^+ \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} CH_3{\cdot}\overset{+}{C}Me{\cdot}CH_2Cl \underset{k'_{-1}}{\overset{k'_1}{\rightleftharpoons}} H^+ + CH_3{\cdot}CMe{:}CHCl \qquad (1)$$

[4] de la Mare and Salama, *J.*, 1956, 3337.
[5] Brown, Kharasch, and Chao, *J. Amer. Chem. Soc.*, 1940, **62**, 3435.

This isomerisation, which is well known to occur in various aqueous acidic media,[6] and can be accompanied by hydration of the double bond, proceeds presumably through such a carbonium ionic intermediate as is indicated in reaction (1).

The final position of equilbrium is determined largely by the conjugation, in the vinylic chloride, of the chlorine atom with the double bond; both chlorides are stabilised also by the hyperconjugation of two approximately equivalent alkyl groups.

Added, July 31st, 1956.—More accurate results for the hydrolysis in water of *tert.*-butyl chloride and 3-chlorobut-1-ene have recently been given and discussed.[7]

Experimental.—Kinetic measurements were made by conventional techniques, described in other papers [5, 4] where methods of specifying solvents and of calculating rate-coefficients are also described. For product analysis, 1 : 2-dichloro-2-methylpropane (200 g.) was refluxed with formic acid (1400 ml.) and water (50 ml.) for *ca.* 6 hr., while a slow stream of nitrogen was bubbled through the solution. The volatile products were collected in traps cooled to −80°, and added to pentane. The mixture was washed with water, with sodium carbonate till neutral, with water again, dried ($CaCl_2$), and fractionally distilled. The following fractions were obtained :

Fraction	Wt. (g.)	B. p.	n_D^{25}	Total Cl (%)	Hydrolysable Cl (%)
1	2·3	37·1—50·1°	1·3584	—	—
2	0·9	50·1—65·1	1·3869	—	0·6
3	1·6	65·1—68·1	1·4090	28·5	2·0
4	3·8	68·1—68·6	1·4203	28·7	2·6
5	1·1	68·6—71·1	1·4204	35·5	3·5
6	0·2	71·7—76·1	1·4204	—	—

The values under the heading " total Cl " were determined by Mr. A. V. Winter of this Department. Those for " hydrolysable Cl " were obtained in the following way. Known weights of the compound were heated in sealed tubes containing excess of alcoholic silver nitrate at 45° for three days; then the remaining silver nitrate was determined by Volhard's method.

The recovered chlorine-containing material clearly contained very little hydrolysable chlorine. The ratio of hydrolysable to total chlorine in fractions 3—5 is 0·09, a value which approximates closely to the equilibrium [5] value of 0·1.

To show that 3-chloro-2-methylpropene, if it had been formed in excess of the equilibrium amount, would not have survived the experimental conditions, 3-chloro-2-methylpropene (25 g.; b. p. 71·5°/760 mm., n_D^{25} 1·4270; hydrolysable Cl, 39·7%) was dissolved in formic acid (950 ml.) and water (50 ml.). The mixture was heated at 66° for 115 hr. These conditions were chosen because it was necessary to ensure that the chloride remained dissolved in the formic acid, and if the reaction mixture had been sealed up and heated at 100°, dangerous pressure would have developed through the acid-catalysed decomposition of formic acid to give carbon monoxide. After this period of heating, which was considered to be fairly equivalent to 6 hr. at 100°, nitrogen was bubbled through the solution, and the volatile products were collected and worked up as before, giving the following fractions :

Fraction	Wt. (g.)	B. p.	n_D^{25}	Total Cl	Hydrolysable Cl
1′	1·3	66·8—68°	1·4126	33·2	2·9
2′	1·4	68	1·4171	33·2	3·6
3′	3·0	Residue	1·4241	39·6	8·2

Under these conditions, isomerisation is clearly almost complete; the ratio of hydrolysable to total Cl is 0·15.

We are indebted to Professor E. D. Hughes, F.R.S., for valuable comments on this manuscript.

William Ramsay and Ralph Forster Laboratories,
University College, Gower St., London, W.C.1. [*Received, June 5th*, 1956.]

[6] Burgin, Hearne, and Rust, *Ind. Eng. Chem.*, 1941, **33**, 385.
[7] Wilputte-Skinert and Fierens, *Bull. Soc. chim. belges*, 1955, **64**, 308.

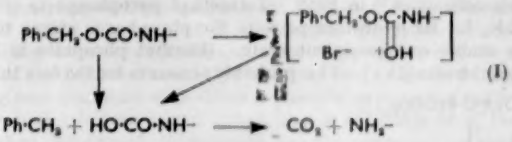
Recent Progress in the Chemistry of Peptides.

THE TILDEN LECTURE, DELIVERED BEFORE THE SOCIETY AT THE IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY, LONDON, ON JANUARY 19TH, 1956, AND AT THE UNIVERSITY, MANCHESTER, ON FEBRUARY 9TH, 1956.

By G. W. KENNER.

INVESTIGATION of peptides began, of course, in 1901, when Emil Fischer and Fourneau synthesised glycylglycine and regarded it as the simplest example of the way in which amino-acids are joined together in proteins.[1] During the nineteen-thirties the peptide theory of protein structure was massively supported by the classical investigations of Max Bergmann, who showed that synthetic peptides are attacked by the various proteolytic enzymes in specific fashions.[2]

Synthesis.—The synthetic peptides required for these studies were mostly prepared by the "carbobenzoxy" (benzyloxycarbonyl) method [3]—Bergmann's great contribution to peptide synthesis. The benzyloxycarbonyl protecting group was removed by hydrogenolysis of the benzyl–oxygen link and consequent decarboxylation of the carbamic acid. An alternative



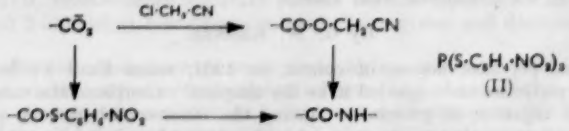
(I)

procedure, which has proved very convenient since its recent introduction,[4] consists in treating the benzyloxycarbonyl derivative with hydrogen bromide in an organic solvent such as acetic acid or nitromethane. The products are benzyl bromide, carbon dioxide, and the hydrobromide of the amino-compound. Presumably the function of the hydrogen bromide is to form an intermediate salt (I), in which the usual sensitivity of the benzyl-carbon atom to nucleophilic attack is greatly enhanced. Another modification of Bergmann's method is to use substituted benzyloxycarbonyl groups in order to obtain more easily crystallised derivatives.[5] Toluene-*p*-sulphonyl was suggested [6] as a protecting group even before discovery of the benzyloxycarbonyl method, but it has been widely used only in recent years since the sodium–liquid ammonia technique [7] has been developed for its removal; ion-exchange resins are valuable aids in working up these reaction mixtures.[8] Toluene-*p*-sulphonyl groups can also be removed with hydrogen bromide in acetic acid containing phenol.[9] A third protecting group, which has been successfully, although less widely, used is phthaloyl.[10,11] This is not an exhaustive catalogue of all the proposed and possible protecting groups, and the availability of this range of groups, which can be removed selectively,[12] will be useful in complex syntheses. The need for amino-protecting groups arises, of course, during extension of the peptide chain by condensation of the carboxyl group at its other end with the amino-group of the addendum.

Hitherto the commonest methods of condensation have involved conversion of the carboxyl group into a mixed anhydride. As this topic was discussed before the Society at a Symposium

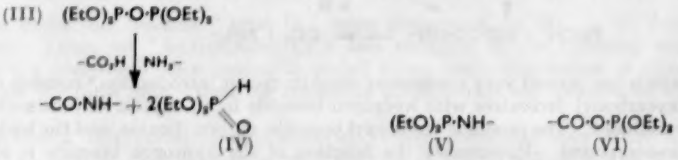
[1] Fischer and Fourneau, *Ber.*, 1901, **34**, 2868.
[2] Cf. Bergmann and Fruton, *Adv. Enzymol.*, 1941, **1**, 63.
[3] Bergmann and Zervas, *Ber.*, 1932, **65**, 1192.
[4] Ben-Ishai and Berger, *J. Org. Chem.*, 1952, **17**, 1564; Anderson, Blodinger, and Welcher, *J. Amer. Chem. Soc.*, 1952, **74**, 5311; Albertson and McKay, *ibid.*, 1953, **75**, 5323.
[5] Channing, Turner, and Young, *Nature*, 1951, **167**, 487; Carpenter and Gish, *J. Amer. Chem. Soc.*, 1952, **74**, 3818.
[6] Schönheimer, *Z. physiol. Chem.*, 1926, **154**, 203.
[7] Du Vigneaud and Behrens, *J. Biol. Chem.*, 1937, **117**, 27.
[8] Swan and du Vigneaud, *J. Amer. Chem. Soc.*, 1954, **76**, 3111; Rudinger, *Coll. Czech. Chem. Comm.*, 1954, **19**, 378.
[9] Weisblat, Magerlein, and Myers, *J. Amer. Chem. Soc.*, 1953, **75**, 3630.
[10] King and Kidd, *J.*, 1949, 3315.
[11] Sheehan and Frank, *J. Amer. Chem. Soc.*, 1949, **71**, 1856; Sheehan, Chapman, and Roth, *ibid.*, 1952, **74**, 3822.
[12] Boissonas and Preitner, *Helv. Chim. Acta*, 1953, **36**, 875.

less than a year ago,[13] I shall not deal with it now, and I shall turn instead to some alternative procedures of recent provenance. The first is very similar in principle; instead of an anhydride, an ester can be used provided that the esterifying group is sufficiently electronegative. This approach has been thoroughly explored by Schwyzer and his colleagues, who have arrived at cyanomethyl as the preferred group.[14] The cyanomethyl esters are prepared from a salt of the acid and chloroacetonitrile, and they react easily with amines in presence of acetic acid.

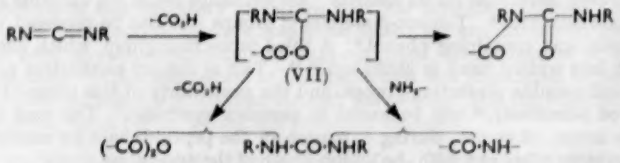


Bodánszky[15] has advocated the use of nitrophenyl esters, but we have preferred to use the *p*-nitrophenyl thiolesters, since these are more reactive and can be prepared directly from the acid by means of tri-*p*-nitrophenyl phosphorotrithioite[16] (II). (Phenyl thiolesters, prepared in a different way, had already been used in similar fashion.[17]) The "activated ester" and the "mixed anhydride" class of synthesis have this in common: activation of the carboxyl group and reaction with the amino-compound in two distinct steps.

A method of condensing the carboxyl and the amino-group in a single stage was supplied by Anderson and his colleagues[18] in 1952. Tetraethyl pyrophosphite (III), their reagent, is an unusual anhydride, for its hydration permits the phosphorus atoms to pass from the tervalent to the more stable quinquevalent state. [Diethyl phosphite is less stable than its tautomer diethyl phosphonate (IV).] This probably accounts for the fact that the corresponding



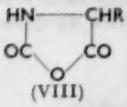
amides (V) yield carboxyamides through reaction with carboxylic acids.[19] The mixed anhydrides (VI), which may be formed from the pyrophosphite and carboxylic acids, react in the normal way with amines,[20] and thus the desired peptide is the product of either reaction path. Different techniques for the exploitation of tervalent phosphorus compounds have been developed by Goldschmidt and his colleagues.[21]



More recently Sheehan and Hess[22] have produced a particularly simple technique of direct condensation. Carbodi-imides[23] generally react with carboxylic acids giving either an *N*-acylurea[24] or the acid anhydride, presumably through intermediate formation of the *O*-acylurea

[13] Kenner, *Chem. Soc. Special Publ.* No. 2, 1955, p. 103.
[14] Schwyzer, Iselin, and Feurer, *Helv. Chim. Acta*, 1955, **38**, 69; Schwyzer, Feurer, Iselin, and Kägi, *ibid.*, p. 80; Iselin, Feurer, and Schwyzer, *ibid.*, p. 1508.
[15] Bodánszky, *Nature*, 1955, **175**, 685; Bodánszky, Szelke, Tömörkény, and Weisz, *Chem. and Ind.*, 1955, 1517.
[16] Farrington, Kenner, and Turner, *Chem. and Ind.*, 1955, 601.
[17] Wieland, Schäfer, and Bokelmann, *Annalen*, 1951, **573**, 99.
[18] Anderson, Blodinger, and Welcher, *J. Amer. Chem. Soc.*, 1952, **74**, 5309.
[19] Anderson, Blodinger, Young, and Welcher, *ibid.*, p. 5304.
[20] Anderson and Young, *ibid.*, p. 5307.
[21] Süs, *Annalen*, 1951, **572**, 96; Goldschmidt and Lautenschlager, *ibid.*, 1953, **580**, 68; Goldschmidt and Obermeier, *ibid.*, 1954, **588**, 24.
[22] Sheehan and Hess, *J. Amer. Chem. Soc.*, 1955, **77**, 1067.
[23] Khorana, *Chem. Rev.*, 1953, **53**, 145.
[24] For some examples in the peptide series, see Khorana, *J.*, 1952, 2081.

(VII). However, in presence of an amine these reaction sequences may be superseded by that leading to the amide. Di*cyclo*hexyl carbodi-imide is thus a promising reagent for peptide synthesis, although considerable quantities of *N*-acylureas have been isolated as by-products in some cases.[25]

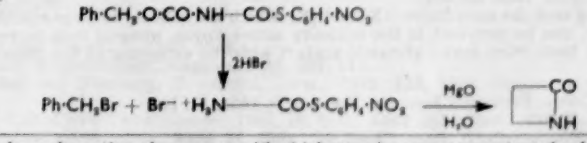


(VIII)

The cyclic *N*-carboxy-α-amino-acid anhydrides ("Leuchs anhydrides") (VIII) have been used in syntheses of quite a different pattern. Although this route can be used for the addition of a single amino-acid residue to a peptide chain,[26] it is better adapted to the production of "poly-α-amino-acids."[27] The mechanism of this process was thoroughly discussed at last year's Symposium.[28]

There is one general point about peptide synthesis which is so important that I make no apology for considering it now despite the previous discussion[13] at the Symposium. Unless the residue concerned is glycine, there is an asymmetric carbon atom next to the carboxyl group undergoing the condensation process. Now, α-acylamino-acids are particularly susceptible to racemisation at this point when the carboxyl group is "activated," for example, by conversion into a mixed anhydride. Indeed racemisation can occur even when apparently it is the amino-group which is activated, as in "phosphite-amide" synthesis.[29] The extent of racemisation depends not only on the type of condensation procedure but also on the nature of the α-acyl substituent. The benzyloxycarbonyl group gives exceptionally resistant derivatives and therefore the safest practice[30] is to confine application of the newer syntheses, which are all, apart from the carbodi-imide method, known to cause racemisation under some conditions, to the benzyloxycarbonylamino-acids and to use the classical azide method for condensation at the carboxyl groups of di- and higher peptides. Such a drastic limitation means almost discarding the new syntheses and accordingly we have made a scrupulous examination of the extent of racemisation caused by our own two methods during the condensation of benzyloxycarbonylglycyl-L-alanine with either L-phenylalanylglycine or its ethyl ester.[31] With the first method,[32] which involves mixed anhydrides of sulphuric acid, racemisation could not be detected at all when dry dimethylformamide was the condensation medium, but in aqueous media there was an appreciable amount, which increased with the pH. However, less than 1% of the product was racemised when the pH was kept below 7 by means of solid magnesium carbonate. Under these conditions the nitrophenyl thiolester method caused much racemisation. This was disappointing, because retention of asymmetry during a different synthesis had been observed earlier.[16] An obvious conclusion is that each condensation should be treated on its own merits, but we believe that the sulphuric anhydride method will be generally free from racemisation during reactions in anhydrous media and we hope that it will also serve well for reactions in aqueous solutions. Theoretical considerations[31] accord with the fact that the thiolesters, which couple more slowly and therefore have a longer exposure to the aqueous media, suffer more racemisation.

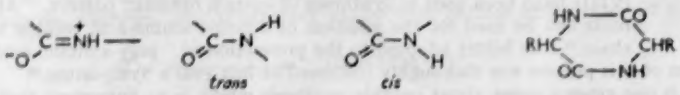
Cyclic Peptides.—Although thiolesters are not likely to be general reagents for peptide synthesis, their stability towards hydrolysis makes them valuable for the synthesis of cyclic peptides,[33] since a terminal amino-group, liberated from its benzyloxycarbonyl derivative by hydrogen bromide, has time to attack the thiolester under conditions of high dilution.* If possible, the ring should be closed at the carboxyl group of a glycine residue in order to avoid racemisation.



* Linear polycondensation also occurs with thiolesters in more concentrated solutions.[34]

[25] Khorana, *Chem. and Ind.*, 1955, 1087.
[26] Bailey, *J.*, 1950, 3461; cf. also Rudinger and Sörm, *Coll. Czech. Chem. Comm.*, 1951, **16**, 214; Zaoral, Rudinger, and Sörm, *ibid.*, 1953, **18**, 530; Zaoral and Rudinger, *ibid.*, 1955, **20**, 1185; Honzl and Rudinger, *ibid.*, p. 1191.
[27] Katchalski, *Adv. Protein Chem.*, 1951, **6**, 123.
[28] Ballard and Bamford, *Chem. Soc. Special Publ.* No. 2, 1955, p. 25.
[29] North and Young, *Chem. and Ind.*, 1955, 1597.
[30] Boissonas, Guttman, Jaquenoud, and Waller, *Helv. Chim. Acta*, 1955, **38**, 1491.
[31] Farrington, Ph.D. Thesis, Cambridge, 1955.
[32] Kenner and Stedman, *J.*, 1952, 2069.
[33] Kenner and Turner, *Chem. and Ind.*, 1955, 602.
[34] Wieland and Schäfer, *Annalen*, 1952, **576**, 104.

The stereochemistry of cyclisation is interesting. Mesomeric participation of the dipolar structure causes an amide to prefer the planar conformation. Of the two possibilities the *trans* is presumably more stable and occurs in open-chain peptides,[35] but there is evidently no serious bar to the *cis*-conformation, for cyclic dipeptides, dioxopiperazines, are formed from dipeptide



esters with notorious ease. A molecular model of a cyclic tripeptide shows that in this too the amide groups must be in the *cis*-form and that there is considerable congestion around the three hydrogen atoms on the α-carbon atoms; this would prohibit the existence of a cyclic tripeptide composed of both D- and L-amino-acids. Models of cyclic tetrapeptides can be constructed with some difficulty using various combinations of *cis*- and *trans*-conformations. All the amide groups are *trans* in the models of the penta- and hexa-peptides and there is no marked congestion. The thiolester cyclisation has been applied to several peptides composed of L-leucine and glycine and the yields of crystalline cyclic product obtained under comparable conditions from the tri-, tetra-, penta-, and hexa-peptides were 16, 2, 44, and 44% respectively.[36] These results agree with our deductions from the models and with the composition of the mixture of cyclic glycine peptides, in which the hexapeptide predominates, obtained from *N*-carboxyglycine anhydride;[37] moreover, *cyclo*hexaglycyl is also the major condensation product from diglycylglycine azide in dilute solution.[37,38] * Results of greater value should be provided by our current investigation of the effect of the asymmetry at the α-carbon atoms in the cyclisation process. The relatively rigid cyclic peptides are themselves stereochemically interesting, particularly with regard to their resistance to peptidases; their study may throw light on the conformation adopted by the peptide during enzymic attack.

Glutamic Acid Peptides.—The general problem of peptide synthesis is sometimes complicated by the side-chain groups. The important case of cystine peptides was discussed at last year's Symposium.[39] Two other amino-acids which present difficulties, histidine[40] and arginine,[41] have recently received attention. I shall only deal now with glutamic acid.

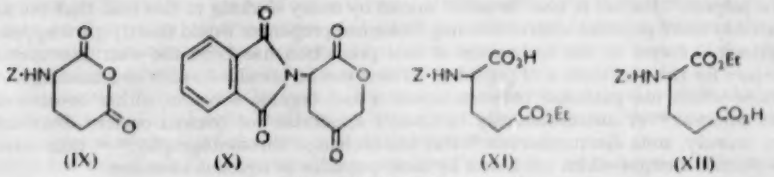
The problem here is to condense selectively either the α- or the γ-carboxyl with the amino-group of a peptide or amino-acid. It is the α-linkage which occurs in proteins, but derivatives in which the γ-carboxyl group is involved in chain formation are well known, namely, glutathione, the fermentation *Lactobacillus casei* factor,[42] and bacterial poly-D-glutamic acid.[43] The classical solution [9] of the α-problem is to use the cyclic anhydride (IX) of benzyloxycarbonyl-L-glutamic acid, which is attacked predominantly at the α-carbonyl group, from which electrons are withdrawn by the neighbouring urethane group. On the other hand, γ-derivatives are formed from the cyclic phthaloyl anhydride (X),[10] owing perhaps to the bulk of the phthalimido-substituent.† However, mixtures are produced, at least from the benzyloxycarbonyl

* [Added in proof.] *cyclo*Tetraglycyl has now been synthesised by Schcoyzer, Iselin, Rittel, and Sieber (*Helv. Chim. Acta*, 1956, **39**, 872).

† It is interesting that the anhydrides (IX) and (X), which are unlikely to be in equilibrium with the isomeric oxazolones, can be prepared in the optically active forms, whereas only racemic anhydrides have been obtained from other acyl-L-glutamic acids [44] with the exception of the trifluoroacetyl compound.[45]

[35] Pauling and Corey, *Fortschr. Chem. org. Naturstoffe*, 1954, **11**, 180.
[36] Turner, Ph.D. Thesis, Cambridge, 1955.
[37] Bamford and Weymouth, *J. Amer. Chem. Soc.*, 1955, **77**, 6368.
[38] Sheehan and Richardson, *ibid.*, 1954, **76**, 6329; Sheehan, Goodman, and Richardson, *ibid.*, 1955, **77**, 6391.
[39] Du Vigneaud, *Chem. Soc. Special Publ.* No. 2, 1955, p. 49.
[40] Holley and Sondheimer, *J. Amer. Chem. Soc.*, 1954, **76**, 1326; Fischer and Whetstone, *ibid.*, p. 5076.
[41] Gish and Carpenter, *ibid.*, 1953, **75**, 5872; Anderson, *ibid.*, p. 6081; Hofmann, Rheiner, and Peckham, *ibid.*, p. 6083; Van Orden and Smith, *J. Biol. Chem.*, 1954, **208**, 751.
[42] Semb, Boothe, Angier, Waller, Mowat, Hutchings, and SubbaRow, *J. Amer. Chem. Soc.*, 1949, **71**, 2310, and previous papers.
[43] Bruckner, Kovács, and Nagy, *J.*, 1953, 148; Waley, *J.*, 1955, 517.
[44] An example and references to other cases are given by Clayton, Kenner, and Sheppard, *J.*, 1956, 371.
[45] Weygand and Leising, *Chem. Ber.*, 1954, **87**, 248.

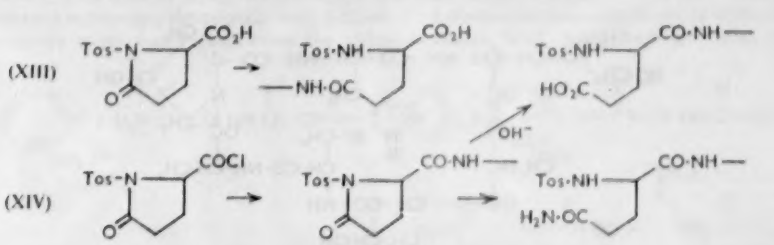
anhydride.[46,47] The crystalline γ- (XI) [48,49] and α-derivative (XII),[48,49] ethyl esters of benzyl oxycarbonyl-L-glutamic acid, can serve as starting materials for other syntheses,[50] but these are attended by the risk of various rearrangements [51] which I cannot discuss now.



(IX) (X) (XI) (XII)

Z = $CH_2Ph{\cdot}O{\cdot}CO-$

Safer routes are available through protection of one carboxyl group as its benzyl ester [52] or by use of the crystalline α-azide γ-amide of benzyloxycarbonylglutamic acid.[53] Nevertheless a completely new approach, which has been made quite independently in two laboratories,[54] is very welcome. It has already proved fruitful and may provide a general solution of the problem. Its basis is the circumstance that the primary dehydration product from toluene-*p*-sulphonyl-L-glutamic acid is not the customary cyclic anhydride but the optically active pyrrolidone (" tosyl pyroglutamic acid ") (XIII).[55] Because this is a diacylimide, the ring



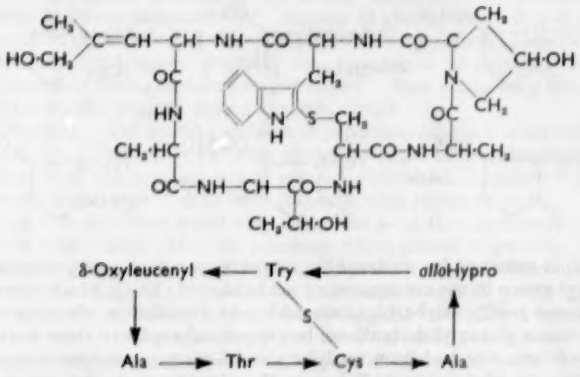
will open when it is attacked by nucleophilic reagents, yet these will prefer to react with the exocyclic carbonyl group in the corresponding acid chloride (XIV), which can also be prepared directly from toluene-*p*-sulphonyl-L-glutamic acid. As sketched in the diagram, ways appear open to all the various glutamyl derivatives, but as yet only some of these have been exploited. Earlier, the pyrrolidone ring had been used for simultaneous protection of the amino- and the γ-carboxyl function in glutamic acid,[56] but in the absence of the toluene-*p*-sulphonyl group opening of the ring is more difficult and not always satisfactory.[57]

Another application of these toluene-*p*-sulphonylpyrrolidones has been to the synthesis of L-proline from L-glutamic acid.[58] The same conversion takes place in micro-organisms, but by a different path.[59]

[46] Le Quesne and Young, *J.*, 1950, 1954.
[47] Wieland and Weidenmüller, *Annalen*, 1955, **597**, 111.
[48] Abderhalden and Nienburg, *Z. physiol. Chem.*, 1933, **219**, 155; Bergmann and Zervas, *ibid.*, 1933, **221**, 53.
[49] Rudinger, *Coll. Czech. Chem. Comm.*, 1951, **16**, 615.
[50] Hegedüs, *Helv. Chim. Acta*, 1948, **31**, 737; Le Quesne and Young, *J.*, 1950, 1959; cf. also Harington and Mead, *Biochem. J.*, 1935, **29**, 1602.
[51] Cason, *J. Org. Chem.*, 1948, **13**, 227; Chase and Hey, *J.*, 1952, 553; Battersby and Robinson, *J.*, 1955, 259; Sachs and Brand, *J. Amer. Chem. Soc.*, 1954, **76**, 1815.
[52] Sachs and Brand, *ibid.*, 1953, **75**, 4608; Clayton, Kenner, and Sheppard, *J.*, 1956, 373.
[53] Sondheimer and Holley, *J. Amer. Chem. Soc.*, 1954, **76**, 2816.
[54] Swan and du Vigneaud, *ibid.*, 1954, **76**, 3110; Rudinger, *Coll. Czech. Chem. Comm.*, 1954, **19**, 375.
[55] Harington and Moggridge, *J.*, 1940, 706.
[56] Angier, Waller, Hutchings, Boothe, Mowat, Semb, and SubbaRow, *J. Amer. Chem. Soc.*, 1950, **72**, 74.
[57] Chambers and Carpenter, *ibid.*, 1955, **77**, 1523.
[58] Pravda and Rudinger, *Coll. Czech. Chem. Comm.*, 1955, **20**, 1.
[59] Ehrensvärd, *Ann. Rev. Biochem.*, 1955, **24**, 282.

Peptides of Natural Origin.—What I have said so far will have shown that considerable ingenuity and effort have been expended during the last half-dozen years on the synthesis of peptides. It may justly be asked what purpose has been behind them. Certainly not the provision of enzyme substrates: the classical methods were adequate, although the new ones may be helpful. Rather it was the belief shared by many working in this field that the number of relatively small peptides with interesting biological properties would shortly grow appreciably. The principal factor in the realisation of this prediction has been the vast improvement in techniques for the purification of peptides. These can be classified under two headings. There are those which use partition between aqueous and organic solvents, either continuously in packed columns [60] or discontinuously in Craig's apparatus for counter-current distribution;[61] others, namely, zone electrophoresis [62] and ion-exchange chromatography,[60,63] take advantage of the electric charges which are borne by most peptides in aqueous solutions.

There are now too many known peptides [64] for me to mention them all individually, and I shall just draw attention to a few examples in each of three groups, classified by biological activity. Amongst the hormones the most completely investigated examples are the insulins and oxytocin. The structures are also known of the two vasopressins [65] and β-corticotropin,[66] one member of the family of peptides composing the adrenocorticotrophic hormone (ACTH). It should not be supposed that all the "protein hormones" will turn out to be peptides with molecular weights less than 6000, like those just mentioned, but nevertheless further progress along these lines can be expected.[67] There are various peptide antibiotics with molecular weights about 1200; the exact structures of gramicidin-S [68] and tyrocidine-A [69] are known and



much progress has recently been made with bacitracin-A.[70] The third group are powerful toxins. Comparatively little is still known about the neurotoxins of snake venoms,[71] but the complete structure of one fungal toxin, phalloidin (molecular weight 770), has been elucidated by the brilliant investigations of T. Wieland.[72]

[60] Campbell and Work, *Brit. Med. Bull.*, 1954, **10**, 196; Porter, *ibid.*, p. 237.
[61] Weisiger, "Organic Analysis," Interscience Publ. Inc., New York, 1954, Vol. II, p. 278; Hecker, "Verteilungsverfahren im Laboratorium," Verlag Chemie, Weinheim, 1955.
[62] Tiselius and Flodin, *Adv. Protein Chem.*, 1953, **8**, 461.
[63] Samuelson, "Ion Exchangers in Analytical Chemistry," Wiley, New York, 1953.
[64] Synge, *Quart Rev.*, 1949, **3**, 245; Bricas and Fromageot, *Adv. Protein Chem.*, 1953, **8**, 1.
[65] Du Vigneaud, Lawler, and Popenoe, *J. Amer. Chem. Soc.*, 1953, **75**, 4880; Acher and Chauvet, *Biochim. Biophys. Acta*, 1953, **12**, 487.
[66] Bell, *J. Amer. Chem. Soc.*, 1954, **76**, 5565; Howard, Shepherd, Eigner, Davies, and Bell, *ibid.*, 1955, **77**, 3419. For the structure of corticotropin-A see White and Landmann, *ibid.*, p. 1711.
[67] Gaddum (ed.), "Polypeptides which stimulate Plain Muscle," Livingstone, Edinburgh, 1955; Peart, *Nature*, 1956, **177**, 132.
[68] Synge, *Biochem. J.*, 1945, **39**, 363; Consden, Gordon, Martin, and Synge, *ibid.*, 1947, **41**, 596.
[69] Paladini and Craig, *J. Amer. Chem. Soc.*, 1954, **76**, 688.
[70] Lockhart, Abraham, and Newton, *Biochem. J.*, 1955, **61**, 534; Weisiger, Hausmann, and Craig, *J. Amer. Chem. Soc.*, 1955, **77**, 731, 3123.
[71] Slotta, *Fortschr. Chem. org. Naturstoffe*, 1955, **12**, 433.
[72] Wieland and Schön, *Annalen*, 1955, **593**, 157.

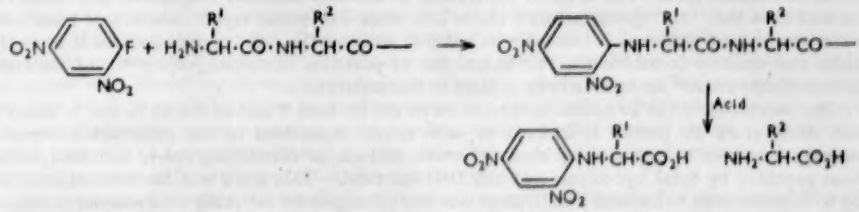
The structure * of phalloidin illustrates the way in which the peptides from lower organisms frequently incorporate amino-acids not found in proteins.[74] Thus, apart from the sulphide cross-link, there is the unique "δ-oxyleucenyl" (2-amino-5-hydroxy-4-methylpent-3-enoyl) residue and the configuration at the secondary hydroxy-group in the pyrrolidine ring is unusual. In other natural products there are residues with usual structures but the D-configuration.

It may be that many other peptides still await detection and isolation because they lack bacteriological or pharmacological activity,[75] but there is little evidence in favour of the obvious possibility that peptides might be definite intermediates in protein synthesis.[76]

The Structures of Insulin and Oxytocin.—The finest example of analytical work in the peptide field is the solution of the insulin problem by Sanger and his colleagues. An adequate account needs a complete lecture, but I shall try to sketch the chief steps.

Insulin has this much to recommend it as a subject of study: it is commercially available in a highly purified form, adequate for virtually all degradations.† Complete purification has been achieved by counter-current distribution [78] and this material has been used for exact analysis of the amino-acid content [79] by the excellent ion-exchange method of Moore and Stein [80] after drastic acid hydrolysis. Analyses had to be made at intervals during the hydrolysis since some amino-acids (serine, threonine, tyrosine) were progressively destroyed, whereas others (*iso*leucine, valine) were liberated only slowly. These phenomena are general and can be compensated by suitable corrections.[81] It is remarkable that a great deal of progress with the structural problem was made before the exact composition of insulin had been determined; indeed the correct amino-acid content had by then been deduced from the degradative studies!

In order to be able to tackle the structural problem, Sanger devised the "DNP" method.[82] This consists in treating the peptide with 1-fluoro-2 : 4-dinitrobenzene, which reacts with amino-groups much more easily than does the chloro-analogue tried much earlier.[83] The newly



formed bond is very stable to acid, although it can be broken by alkali,[84] and consequently the amino-acid residues with free amino-groups can be identified as their yellow dinitrophenyl

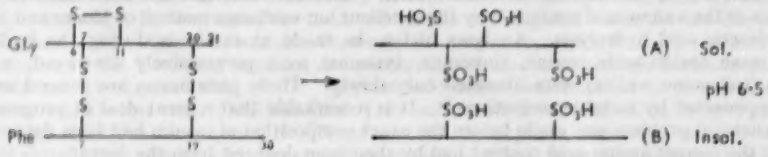
* Comparison of the two formulæ shows how much more expressive and economical is the short hand [73] now widely used. The literal symbols stand for amino-acid residues, *e.g.*, Ala for alany –NH·CH(CH$_3$)·CO–. An arrow symbolises a bond *from* a carbonyl of one residue *to* the imino-group o another. Where dots are used instead of arrows in other formulæ, the residues are always arranged with their imino-groups on the left. Chains ought strictly to be terminated by H· and ·OH, or $^+H_3$· and ·O$^-$, if the end-groups are free, but these terminations are usually omitted in reporting analytical work. Z means benzyloxycarbonyl.

† Cattle, pigs, and sheep produce insulins of slightly different composition. The differences affect only a single region of three amino-acid residues [77] and the following remarks apply to all three substances. That from cattle was used throughout Sanger's work, except for the comparison of species.

[73] Brand and Edsall, *Ann. Rev. Biochem.*, 1947, **16**, 223; Erlanger and Brand, *J. Amer. Chem. Soc.*, 1951, **73**, 3509.
[74] Bricas and Fromageot, *Adv. Protein Chem.*, 1953, **8**, 6.
[75] Synge, "The Chemical Structure of Proteins" (ed. Wolstenholme and Cameron for the Ciba Foundation), Churchill, London, 1953, p. 43.
[76] Ehrensvärd, *Ann. Rev. Biochem.*, 1955, **24**, 300.
[77] Brown, Sanger, and Kitai, *Biochem. J.*, 1955, **60**, 556.
[78] Harfenist and Craig, *J. Amer. Chem. Soc.*, 1952, **74**, 3083.
[79] Harfenist, *ibid.*, 1953, **75**, 5528.
[80] Moore and Stein, *J. Biol. Chem.*, 1954, **211**, 893, and earlier papers.
[81] Smith, Stockell, and Kimmel, *J. Biol. Chem.*, 1954, **207**, 551; Hirs, Stein, and Moore, *ibid.*, **211**, 941.
[82] Sanger, *Biochem. J.*, 1945, **39**, 507; Levy, "Methods of Biochemical Analysis" (ed. Glick), Interscience Publ. Inc., New York, 1955, Vol. II, p. 360.
[83] Abderhalden and Stix, *Z. physiol. Chem.*, 1923, **129**, 143.
[84] Lowther, *Nature*, 1951, **167**, 767.

derivatives, which can be chromatographed on either silica gel [83] or paper.[85] The free amino-groups in insulin turned out to be those of glycine and phenylalanine and the ε-group of lysine, a diamino-monocarboxylic acid, and equivalent amounts of them were detected. Later, using counter-current distribution, Harfenist and Craig [86] isolated the mono(dinitrophenyl) derivative of insulin from partial reaction with fluorodinitrobenzene and showed that the intensity of its absorption at 3500 Å corresponded to a molecular weight of about 6500. In contrast, almost all the usual physical methods had dealt with aggregates and had given values of at least 12,000, which had been regarded as the true molecular weight. The correct figure for insulin from cattle is 5733.

Sanger deduced that there are in insulin two kinds of peptide chain, with terminal glycine and phenylalanine residues respectively, and that these are linked by the disulphide bridges of cystine residues. The truth of this belief was demonstrated by oxidising insulin with performic acid and separating the two chains.[87] The actual arrangement of the amino-acid residues in



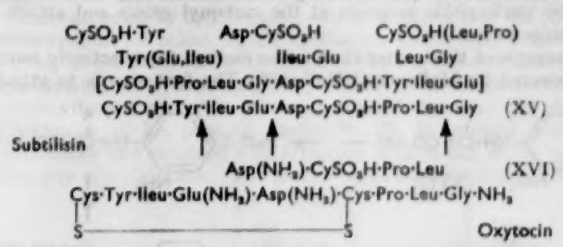
insulin is outlined in the diagram; the numbers refer to the location of different residues along each chain and for this purpose each half of a cystine residue is counted separately. The diagram shows how two of the disulphide bridges are used for interchain links and the third for an intrachain link. The original separation of the two oxidised fragments was based on the fact that the " B " (phenylalanyl) chain has, after oxidation, equal numbers of basic and acidic groups and therefore is insoluble at pH 6·5, whereas the " A " (glycyl) chain is strongly acidic and remains in solution. The techniques of partition chromatography [88] and counter-current distribution [89] have since been applied to this separation.

The sequences of the 30 amino-acid residues in the B chain [90] and of the 21 in the A chain [91] were determined by partial hydrolysis of each chain, separation of the resultant extremely complex mixtures of peptides by electrophoresis and paper chromatography, and analysis of these peptides by total hydrolysis and the DNP method. This work was far too intricate for me to describe here. Instead I shall illustrate the principles by referring to a simpler problem, the structure of oxytocin, a posterior-pituitary hormone. Oxytocin was isolated by du Vigneaud and his colleagues,[92] who showed that it contains one cystine residue together with equivalent amounts of seven other amino-acids and three molecules of ammonia.[93] In addition, they oxidised oxytocin with performic acid and showed that the product contained, instead of the cystine, two residues of cysteic acid and still seven other residues and three molecules of ammonia.[94] Performic-oxidised oxytocin thus presented the same problem as did the B chain of insulin, except that there were 9 residues to be placed in sequence instead of 30.

Tuppy and Michl [95] solved this problem in the fashion in which Sanger and Tuppy had already solved the larger one. Partial acidic hydrolysis gave a mixture of the two tri- and four di-peptides shown below; the parentheses in the tripeptide structures enclose residues of undetermined sequence, because the DNP method identified only the *N*-terminal residue (*i.e.*, that with a free amino-group). With one more piece of information, namely, that the *N*-terminal residue is cysteic acid, these fragments could be reassembled in only the two sequences shown. Enzymic degradation with subtilisin, which attacked the chain at the three points marked by arrows, provided additional degradation products including the tetrapeptide

[85] Biserte and Osteux, *Bull. Soc. Chim. biol.*, 1951, **33**, 50; Levy, *Nature*, 1954, **174**, 126.
[86] Harfenist and Craig, *J. Amer. Chem. Soc.*, 1952, **74**, 3087.
[87] Sanger, *Biochem. J.*, 1949, **44**, 126.
[88] Andersen, *Compt. rend. Trav. Lab. Carlsberg*, 1954, **29**, 49.
[89] Pierce, *J. Amer. Chem. Soc.*, 1955, **77**, 184.
[90] Sanger and Tuppy, *Biochem. J.*, 1951, **49**, 463, 481.
[91] Sanger and Thompson, *ibid.*, 1953, **53**, 353, 366.
[92] Livermore and du Vigneaud, *J. Biol. Chem.*, 1949, **180**, 365; Pierce, Gordon, and du Vigneaud, *ibid.*, 1952, **199**, 929.
[93] Pierce and du Vigneaud, *ibid.*, 1950, **182**, 359; **186**, 77.
[94] Mueller, Pierce, Davoll, and du Vigneaud, *ibid.*, 1951, **191**, 309.
[95] Tuppy and Michl, *Monatsh.*, 1953, **84**, 1011.

(XVI).* This was inconsistent with the nonapeptide sequence in square brackets and confirmed the alternative (XV). By disposing of the three molecules of ammonia on the "spare" carboxyl groups and reconstituting the disulphide bridge, the complete structure of oxytocin is reached with the ambiguity that no evidence has been presented concerning the α- or γ- and α- or β-nature of the glutamyl and the aspartyl link respectively. The same stage was reached independently after a more elaborate series of degradations by du Vigneaud and his colleagues,[96]



but they carried the matter further. By a brilliant total synthesis they prepared material with αα-linkages in the chain and showed that it was identical with the isolated hormone.[97] Those who know Dr. du Vigneaud's own account [39] of this work last year will not wish for mine. I shall do no more than mention that the synthesis depended on protection of the sulphur atoms as benzyl thiolesters [98] and on the "pyrophosphite" [18] and the "tosylpyroglutamyl" [54] method which I have already discussed. Active material has since been synthesised in two other laboratories,[30, 99] but the purification does not seem to have been completed in these cases.

Returning to insulin—the structures of the A and the B chain were completely defined by the products of acidic and enzymic hydrolyses,[90, 91, 100] but there were several possible arrangements of the disulphide bonds. Distinction between these was made difficult by interchange amongst the mixed disulphides, which can occur by two mechanisms,[101] but nevertheless suitable conditions were found for partial hydrolysis without interchange and at last the picture was complete.[102] It is hardly possible to overemphasise the magnitude of this achievement: apart from structures with many repeating units, insulin, containing 254 carbon atoms, is by far the largest molecule of known structure. On the other hand, now that this barrier has been surmounted progress with yet larger molecules can be expected.

The question of whether the synthesis of insulin is around the corner has been asked [103] and answered.[104] A major difficulty is that no-one has yet been able to reduce the disulphide bonds of insulin *reversibly*; the tendency of two chains to arrange themselves in the antiparallel fashion may be the cause of the trouble.[105] Consequently the type of synthesis involving oxidation of a reduced form of the hormone, which succeeded with oxytocin, cannot be applied, and the synthesis of insulin must await the development of new approaches to synthetic peptides of cystine. Probably the next stage in the synthesis of polypeptide hormones will be the synthesis of the biologically active fragment of corticotropin which contains 28 amino-acid residues. In this instance the cystine problem is absent, but in compensation there are others.

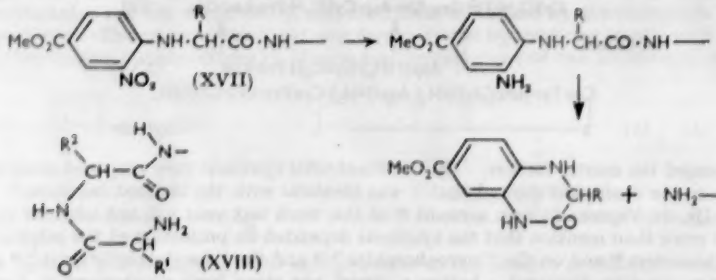
Reactions.—My account of structural analysis of two hormones has, I hope, demonstrated both that the partial hydrolysis method [106] is extremely powerful in the hands of a master of the art and that it can be very complicated. For this reason considerable attention has been paid to possible methods of specific degradation. The proteolytic enzymes have already been used to supplement the stock of acidic-degradation products,[90, 91, 95] and they are likely to be used still more in the future, particularly since highly purified enzyme preparations can now be

* The amide groups, which were lost in the acidic hydrolysis, survived enzymic degradation.

[96] Du Vigneaud, Ressler, and Trippett, *J. Biol. Chem.*, 1953, **205**, 949.
[97] Du Vigneaud, Ressler, Swan, Roberts, and Katsoyannis, *J. Amer. Chem. Soc.*, 1954, **76**, 3115.
[98] Loring and du Vigneaud, *J. Biol. Chem.*, 1935, **111**, 385.
[99] Honzl and Rudinger, *Coll. Czech. Chem. Comm.*, 1955, **20**, 1190.
[100] Sanger, Thompson, and Kitai, *Biochem. J.*, 1955, **59**, 509.
[101] Ryle and Sanger, *ibid.*, 1955, **60**, 535.
[102] Ryle, Sanger, Smith, and Kitai, *ibid.*, 541.
[103] Harington, *Chem. Soc. Special Publ. No.* 2, 1955, p. 64.
[104] Du Vigneaud, *ibid.*, p. 65.
[105] Rydon, *ibid.*, p. 66.
[106] Consden, Gordon, Martin, and Synge, *Biochem. J.*, 1947, **41**, 596; Sanger, *Adv. Protein Chem.*, 1952, **7**, 12.

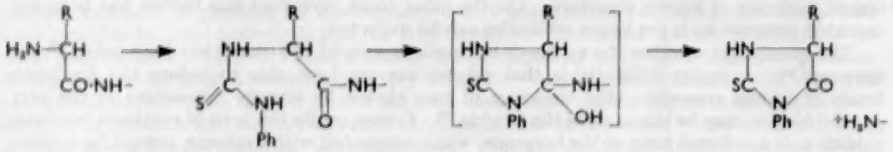
bought. Also many schemes for specific degradation without enzymes have been devised and tested with simple peptides. However, only one of these, that due to Edman,[107] has actually been used to any extent in structural anaylsis.[66, 72, 96, 108] Consequently the main result of these studies has been, in my view, the demonstration that, although the amide group in peptides is normally inert, it can be brought into reaction under very mild conditions provided that the environment is suitable. These reactions of the amide group can be classified under two headings, attack by nucleophilic reagents at the carbonyl group and attack by electrophilic reagents at the nitrogen atom.

An excellent example of the former class is the method for selectively removing the *N*-terminal residue discovered by Holley and Holley.[109] The first step is to attach a 4-methoxy-

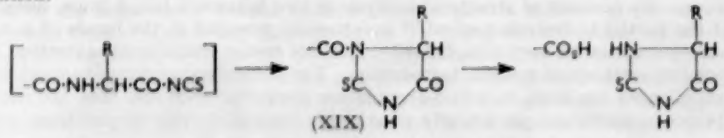


(XVII) (XVIII)

carbonylnitrophenyl group by means of the appropriate fluoro-reagent. Reduction of the intermediate (XVII) then generates an amino-group in a favourable position for attack on the neighbouring amide group and thus liberation of the degraded peptide. In the simple examples described this cyclisation was complete in five hours at room temperature in neutral solution. In contrast, typical conditions for the *partial* hydrolysis of polypeptides are treatment with concentrated hydrochloric acid at 37° for three days or with 0·2N-sodium hydroxide at 100° for five hours. It may well be asked how peptides themselves can be stable, since the terminal amino-group might likewise attack the neighbouring peptide bond forming a dioxopiperazine.



This reaction does occur, but only during very drastic heating in phenolic solvents.[110] At least part of the comparative slowness of this reaction can be ascribed to the necessity, indicated in formula (XVIII), of bringing the terminal amide group into the unfavourable *cis*-conformation.



(XIX)

The intermediate in Edman's degradation[107] is the phenylthioureido-derivative of the peptide. When hydrogen chloride is bubbled into solutions of these intermediates in nitromethane,* the hydrochlorides of the degraded peptides are soon precipitated and the *N*-terminal residue is split off as its phenylthiohydantoin. Rather similar schemes have been devised

* With insoluble compounds aqueous solutions may be used with somewhat less satisfactory results.

[107] Edman, *Acta Chem. Scand.*, 1950, **4**, 283; Landmann, Drake, and Dillaha, *J. Amer. Chem. Soc.*, 1953, **75**, 3638; Fraenkel-Conrat, "Methods of Biochemical Analysis" (ed. Glick), Interscience Publ. Inc., New York, 1955, Vol. II, p. 383.

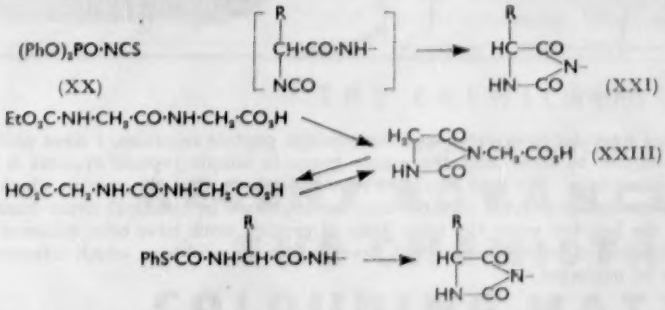
[108] Popenoe and du Vigneaud, *J. Biol. Chem.*, 1953, **205**, 133; Thompson, *ibid.*, 1954, **208**, 565.

[109] Holley and Holley, *J. Amer. Chem. Soc.*, 1952, **74**, 5445.

[110] Lichtenstein, *ibid.*, 1938, **60**, 560; Rydon and Smith, *J.*, 1955, 2542.

by Khorana and myself [111] and by Elmore and Toseland.[112] Another, which I regret that I have not time to describe, was discovered at the same time as Edman's by the late A. L. Levy [113] and was developed by him and Léonis in the most elegant way.[114] *

The second class of reactions is well illustrated by a method for selective removal of the amino-acid residue with a free carboxyl group, the *C*-terminal residue.[115] When the carboxyl group is converted into an acyl *iso*thiocyanate, this cyclises spontaneously to an acylthiohydantoin (XIX), which can be easily hydrolysed. We have shown that the phosphate compound (XX) is an effective reagent for achieving the cyclisation under mild conditions.[116] Similarly, when the amino-group at the other end of the peptide chain is converted into an *iso*cyanate, the isolated product is the isomeric hydantoin (XXI), formed by electrophilic attack of the carbonyl group on the amide-nitrogen atom.[117] A closely related reaction was discovered by Emil Fischer at the beginning of his peptide studies.[118] He hydrolysed ethoxycarbonylglycylglycine (XXII) with alkali and obtained a dicarboxylic acid, which to his surprise did not lose carbon dioxide and give glycylglycine. The simple carbamic acid formula was soon disproved



by esterification to an isomer of ethoxycarbonylglycylglycine ethyl ester, but it was not until 1928 that the mystery was solved.[119] The alkali catalyses condensation between the urethane and the amide group, and the resultant hydantoin (XXIII) is then hydrolysed. Wessely, Schlögl, and their colleagues [120] have used this reaction for structural work. It occurs under rather drastic conditions but the similar elimination of thiophenol from phenylthiocarbonyl peptides takes place very easily and the hydantoin can be isolated.[121]

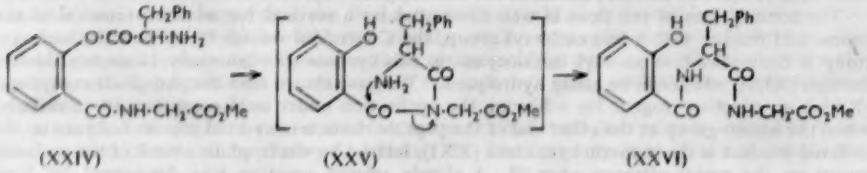
A remarkable rearrangement, which can be regarded as involving both types of reaction, has recently been discovered by Brenner *et al.*[122] The salicylic acid derivative (XXIV) easily isomerises to (XXVI). This becomes less mysterious of we remember that *O*-acetylsalicylamide easily rearranges to *N*-acetylsalicylamide.[123] The analogous rearrangement of (XXIV) would produce the diacylimide (XXV), in which the amino-group is very favourably placed for nucleophilic attack on the salicyl carbonyl group. This interpretation † may be too naïve, and

* [Added in proof.] The similarity of these four schemes is even greater than the above formulæ suggest. The *sulphur* atom first attacks the neighbouring amide group in the phenylthioureido-peptides (Edman, *Nature*, 1956, **177**, 667).

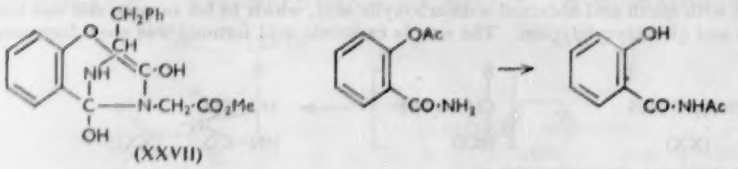
† The same interpretation has now been published by Wieland.[124]

[111] Kenner and Khorana, *J.*, 1952, 2076.
[112] Elmore and Toseland, *J.*, 1954, 4533.
[113] Levy, *J.*, 1950, 404; 1954, 4711.
[114] Léonis and Levy, *Compt. rend. Trav. Lab. Carlsberg*, 1954, **29**, 57, 87.
[115] Schlack and Kumpf, *Z. physiol. Chem.*, 1926, **154**, 125.
[116] Kenner, Khorana, and Stedman, *J.*, 1953, 673.
[117] Goldschmidt and Wick, *Annalen*, 1952, **575**, 217.
[118] Fischer, *Ber.*, 1902, **35**, 1097; 1903, **36**, 2097.
[119] Wessely and Kemm, *Z. physiol. Chem.*, 1928, **174**, 306; Wessely, Kemm, and Mayer, *ibid.*, **180**, 64.
[120] Wessely, Schlögl, and Korger, *Monatsh.*, 1952, **83**, 1156; Wessely, Schlögl, and Wawersich, *ibid.*, p. 1426; Schlögl, Wessely, and Wawersich, *ibid.*, 1954, **85**, 957.
[121] Lindenmann, Khan, and Hofmann, *J. Amer. Chem. Soc.*, 1952, **74**, 476; Wessely, Schlögl, and Wawersich, *Monatsh.*, 1952, **83**, 1439.
[122] Brenner, Zimmerman, Wehrmüller, Quitt, and Photaki, *Experientia*, 1955, **10**, 397.
[123] Auwers, *Ber.*, 1905, **38**, 3256; McConnan and Titherley, *J.*, 1906, **89**, 1318; Anschütz, Aschenberg, Kuckertz, Krone, Riepenkröger, and Zerbe, *Annalen*, 1925, **442**, 18.
[124] Wieland, Lang, and Liebsch, *Annalen*, 1955, **597**, 227.

indeed Brenner prefers to consider (XXVII) as the intermediate, but these alternatives are actually quite closely related.



(XXIV) (XXV) (XXVI)



(XXVII)

Although I have far from exhausted the stock of peptide reactions, I have probably given sufficient examples to show that the amide group in simple peptide systems is reactive in suitable environments. We may therefore reasonably hope that the way in which the amide group reacts on certain enzyme surfaces may be explained in chemical terms during the next decade. In the last few years the main aims of peptide work have been different from those of the era dominated by Bergmann, but nevertheless the problems which interested him are not likely to be neglected.

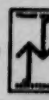
I am very grateful to Sir Alexander Todd, F.R.S., who has most generously given me every opportunity and encouragement to develop my interest in peptides.

Supplied to LABORATORIES THE WORLD OVER

BEATSON CLARK BOTTLES

Dustproof Stoppered reagents

When ordering your Laboratory requirements be sure to specify Beatson Clark Dustproof Stoppered Reagent Bottles.

"The Sign of a  *Good Bottle"*

BEATSON, CLARK & CO. LTD.
GLASS BOTTLE MANUFACTURERS
ROTHERHAM *Established 1751* YORKS

THE CHEMICAL SOCIETY

'SPECIAL PUBLICATION' NO. 4

RECENT ADVANCES IN THE CHEMISTRY OF COLOURING MATTERS

This report of a Symposium held in London on 2nd February, 1956, is the fourth in The Chemical Society's series of Special Publications. The following are the main contributions:

"Steric Effects in Azo and Indigo Dyes," by Wallace R. Brode (Washington).

"*cis-trans*-Isomerism in Azo-dyes," by E. Atherton and R. H. Peters.

"Synthesis of Azaporphins and Related Macrocycles," by J. A. Elvidge (Imperial College).

"Synthetic Carotenoids," by O. Isler, H. Lindlar, M. Montavon, R. Rüegg, G. Saucy, and P. Zeller (Basle).

"Modern Theories of Colour," by M. J. S. Dewar (London).

In addition to the above papers, much information is given in the report of the discussion, which is included in the publication.

Price: 15s.

THE CHEMICAL SOCIETY, BURLINGTON HOUSE, LONDON W.1.

THE WORLD'S GREATEST BOOKSHOP

FOYLES
FOR BOOKS

NEW, SECONDHAND AND RARE
Books

FAMED CENTRE FOR
Technical Books

119-125 CHARING CROSS ROAD, LONDON, W.C.2
GERrard 5660 (20 lines) * Open 9-6 (inc. Sat.)
Two minutes from Tottenham Court Rd. Station

LABORATORY BDH CHEMICALS

N-Methyl-N-nitroso-toluene-p-sulphonamide

$CH_3.C_6H_4.SO_2.N(CH_3).NO$

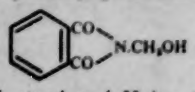
Diazomethane, well known as a valuable and versatile reagent, can be generated easily and safely in solution in ether or in ether and alcohol by treating *N*-methyl-*N*-nitroso-toluene-*p*-sulphonamide with potassium hydroxide in a suitable medium (de Boer and Backer, *Proc. Koninkl. Ned. Akad. Wetenschap.*, 1952, **55B**, 444; *Rec. trav. chim.*, 1954, **73**, 229).

The sulphonamide is issued in very pale yellow crystals, melting point 58-60°C.

10 g 6/6 25 g 13/- 100 g 44/6

Packages extra, returnable

N-Hydroxy-methyl-phthalimide



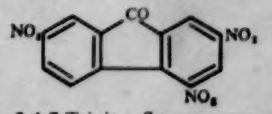
Winstead and Heine (*J. Amer. Chem. Soc.*, 1955, **77**, 1913) have shown that *N*-hydroxy-methyl-phthalimide is a valuable reagent for the identification of amines. The amine to be identified is refluxed with a 10% solution of hydroxy-methyl-phthalimide in 80% ethanol for ½-2 hours and the *N*-arylamino-methyl-phthalimide separates as a crystalline product on cooling. The thirty derivatives prepared by Winstead and Heine melt in the range 112°C to 242°C.

N-Hydroxy-methyl-phthalimide is supplied as an off-white, crystalline powder, melting point 142-144°C.

5 g 3/9 10 g 6/9 25 g 13/3

Packages included

2:4:7-Trinitro-fluorenone



2:4:7-Trinitro-fluorenone, supplied as a pale yellow crystalline powder, melting point 175-6°C, forms stable complexes with a wide variety of aromatic hydrocarbons and derivatives. The complexes are readily prepared and generally melt sharply without decomposition. Apart from their use for identification, they can be employed in purifying certain aromatic hydrocarbons, since the hydrocarbon portion of the complex can be recovered by passing a solution of the complex over activated alumina. Alternatively, the complex may be reduced, giving an acid-soluble product from the trinitro-fluorenone moiety.

There are references in the literature to over a hundred substances known to form complexes with 2:4:7-trinitro-fluorenone. A bibliography will be supplied on application.

1 g 4/9 5 g 17/3 10 g 33/-

Packages included

THE BRITISH DRUG HOUSES LTD.
B.D.H. LABORATORY CHEMICALS GROUP
POOLE DORSET

MH/T/LC/561g

Printed in Great Britain by Richard Clay and Company, Ltd., Bungay, Suffolk.